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EDITORIAL NOTES.

AT the meeting on 16th May last the Geological Society of London elected a large number of Foreign Members and Foreign Correspondents. We believe that this is the first election of the kind since the war, so that the numbers of these two categories had undergone considerable reductions. The following are the names of those elected. *Foreign Members*: Prof. L. Cayeux, Paris; Prof. J. M. Clarke, Albany, N.Y.; Prof. H. Douvillé, Paris; Prof. W. Lindgren, Boston, Mass. *Foreign Correspondents*: Prof. E. Argand, Neuchâtel; Prof. L. W. Collet, Geneva; Prof. R. A. Daly, Harvard; Prof. G. Delépine, Lille; Prof. P. Fourmarier, Liége; Prof. V. M. Goldschmidt, Kristiania; Prof. T. G. Halle, Stockholm; Prof. J. F. Kemp, New York; Prof. C. F. Kolderup, Bergen; Prof. C. I. Lisson, Lima; Prof. G. A. F. Molengraaf, Delft; Dr. A. Renier, Brussels; Prof. P. Termier, Paris; Dr. F. E. Wright, Washington.

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WE desire here to call special attention to the publication by the Geological Society of the list of Geological Literature added to the Society's Library in the years 1915–19, thus bringing the series to completeness and supplying a long-felt want which has been a handicap to geological research and advanced teaching for some time past. It is unnecessary at this date to comment on the usefulness of these publications. In this case the compilation is due to Mr. T. H. D. La Touche: the catalogue runs to 545 pages, of which 313 are devoted to a bibliography under names of authors, the rest being a remarkably complete subject-index. The price to Fellows is 7*s.* 6*d.*, to the general public 10*s.* Our object in mentioning this subject here is to express the hope that all who can will purchase a copy of this work, which has been brought out at a great expense to the Society; it is incumbent on all geologists to lend their support to this enterprise and thus enable the Society to recoup its heavy outlay, which under present conditions can ill be afforded.

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LAST month an appeal was made in these columns on behalf of a thoroughly deserving object, the Geological Department of University College, Reading. This month it is our pleasing duty to chronicle a generous gift to another geological institution for teaching and research. Sir William Herdman has given £20,000 to the University of Liverpool for a building for the Department of Geology. This building is to be a memorial to the late Lady Herdman, who in 1916 gave jointly with Sir William a sum of £10,000 to endow a Chair of Geology in memory of their son, who fell in the battle of the Somme.

ORIGINAL ARTICLES.

The High Plateau of Brazil.

By Robert R. Walls, M.A., B.Sc., F.R.S.G.S.

(WITH PLATE XIII.)

THE High Plateau is a rather ill-defined region occupying the south-eastern portion of Brazil. It rises abruptly from the south-east coast but slopes off very gradually to the north and west. In consequence the rivers flowing north and west are of great length and importance in navigation. Those flowing south are useless for navigation though of great importance for water power. An interesting exceptional river is the Parahyba flowing east and parallel to the south-east coast-line curve. The geology of the whole region is essentially granite and gneiss with curiously metamorphosed quartzites and schists. The accompanying map was made by the writer during some explorations carried out over this region in 1919, and as some of the points studied and already published (1), (2)[1] were new and surprising to geological science, the following general description is added.

The Archæan gneiss reaches almost to the coast leaving only a very narrow margin of sedimentary rocks. The granite and gneiss have many local modifications and no very useful generalizations can be made regarding them. Sometimes the granite is distinctly intrusive into the gneiss, and sometimes a true line of demarcation can scarcely be drawn between them. Pegmatite and quartz veins are common. Schorl-granite appears to be particularly abundant, and some of the gneiss under the microscope proved to contain a considerable amount of cordierite. Monazite is also known to occur in the gneiss but is chiefly worked from the sands round the coast, the result of the weathering down of the rocks of the plateau.

The escarpment of the plateau is known as the Serra do Mar or Coast Range. The Serra do Mar is clearly marked off as an individual ridge by the valley of the River Parahyba on its northern edge. North of the River Parahyba lies the next range, the Serra da Mantiqueira (7). This can scarcely be called a separate mountain ridge or Serra proper as it is really the edge of the plateau again. Its northern slope is so gradual as to be almost lost. The name Serra is thus often used loosely in Brazilian geography. In the accompanying plate a view is given of the valley of the Parahyba, and the Serra da Mantiqueira to the north. The River Parahyba has scooped a huge trench right across the plateau and left the Serra do Mar to the south as a real Serra or mountain ridge of denudation.

Besides the gneiss and granite there is also included in the Brazilian

[1] Figures in parentheses refer to Bibliography at end of paper.

Archæan complex several more basic rocks and also metamorphic rocks and sediments. The more basic rocks appear to be in the nature of lodes, whereas the metamorphosed sediments are in general

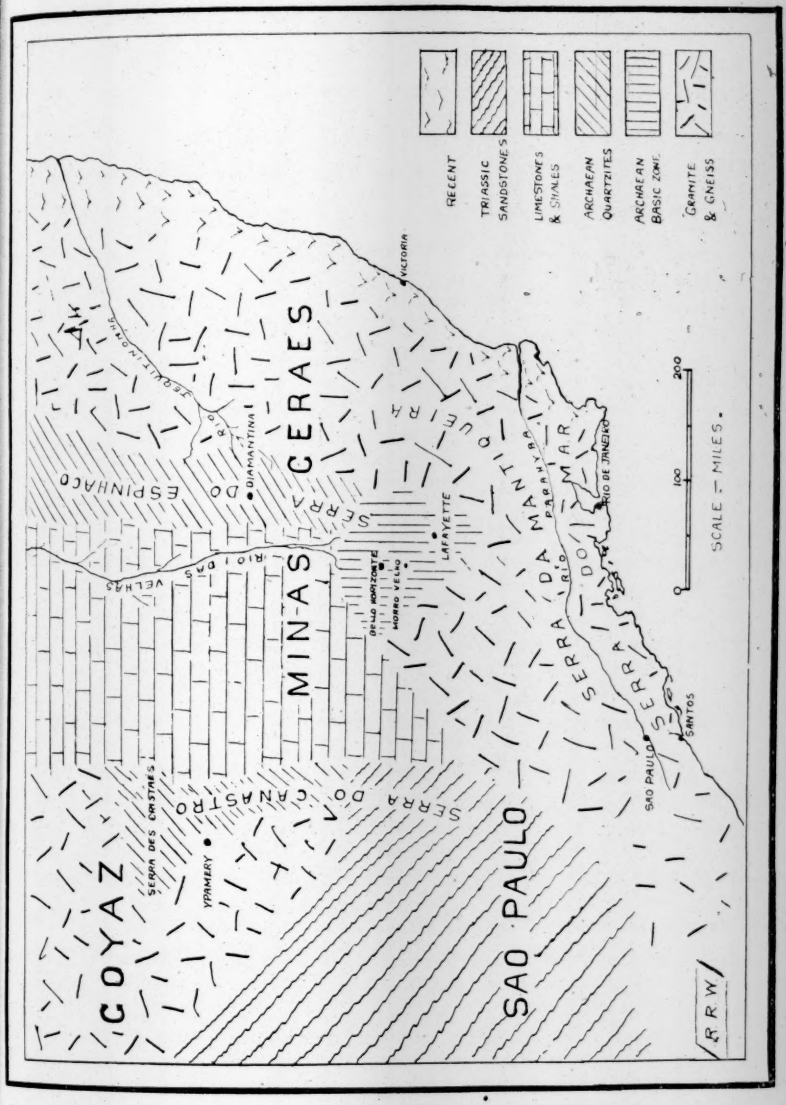

Fig. 1.—Geological map of South-Eastern Brazil.

tilted into the gneiss by a complicated system of thrust faults. With several metamorphic rocks it would be difficult to say whether they occupied lodes or tilted planes of sedimentation. Among the lodes

proper may be mentioned the gold mine of the St. John del Rey Co. at Morro Velho, in the State of Minas Geraes. This lode, which is rich in sulphides, dips at an angle of 45° and in 1919 was being worked at a depth of over 6,000 feet. The percentage of gold was found to be increasing with the depth. Besides gold, silver, sulphur, arsenic, copper, lead, and antimony are also extracted. Among the metamorphic rocks and sediments which appear to have been let down into the gneiss by thrust faults may be mentioned specially the manganese ores of Lafayette and neighbourhood which came so much into prominence during the war. Many of the earthy iron ores appear to be of this nature also. The geology of this region of lodes and thrust faults has not yet been worked out and it is not possible to draw any conclusions with regard to the tectonics of the region where they occur.

The country around Bello Horizonte, the capital of Minas Geraes, is well watered and scored by deep river valleys. A considerable amount of lateritization of the ancient rocks in this district has taken place and reports of considerable deposits of laterite and bauxite have been announced. The rivers throughout the whole plateau abound in clays of varying composition, and the manufacture of pottery, tiles, and pipes is a thriving and growing industry in practically all the larger river valleys.

Running north from the Serra da Mantiqueira is the Serra do Espinhaco (5), or Backbone Ridge of Brazil. It is the highest ridge of the plateau and the real watershed of the area. Its average height is perhaps 5,000 feet or so and it is capped throughout almost its entire length by quartzites. These quartzites, especially in the southern part of the range, are very regularly and horizontally bedded, though farther north they are reported to be tilted and folded. But they are metamorphosed locally into many different forms whose relationships are very puzzling to the field geologist. They have been mapped by different geologists as different beds in a series, but in no two localities can these beds be correlated. J. C. Branner, in his excellent work on the *Outlines of the Geology of Brazil*, gives several different summaries of the sequence of the beds in different localities by different geologists. The difficulties of the field geologist in Brazil have not been lessened by the introduction of new terms of very loose definition such as Itacolumite and Itabirite (5) for varieties of the quartzites. Some of the varieties of the quartzite studied by the writer at first hand are so peculiar as to deserve fuller description here.

Ripple marks appeared on many of the brown varieties of quartzite. These generally showed remarkably regular bedding planes, but joints were uncommon. The sand grains were all cemented in secondary quartz and the quartzites were exceedingly hard. One particularly fine example was a broad bed exposed on the trail, and though scratched all over by horses' hoofs still showed clearly and distinctly the original ripple marks. Another variety

of the brown quartzite in which the writer never noticed ripple marks was remarkable for the prominence of its joint planes which broke up the bedded rock into huge castellated structures and towers, a typical example of which is shown in the accompanying plate.

In another locality the quartzite was pure white, and was locally called Marmor (Marble). It was not crystalline like vein quartz, but indeed strongly resembled a coarse, gritty marble, peculiar in this, that over vast stretches of country there was not a single black mark nor vein upon it. A sample of this was brought home and gave the following analysis :

SiO_2 . . .	90·17
Al_2O_3 . . .	1·85
Fe_2O_3 . . .	1·0*
CaO . . .	3·0
MgO . . .	·18
K_2O . . .	·67
Loss on Ignition .	2·65
	99·52

* The ferric oxide was evidently introduced as the sample was put into a tin box, nothing else being available at the time.

But perhaps the most remarkable modification of all was the conversion of the quartzite into Rock Crystal on a large scale. This has already been described more fully elsewhere (1). Suffice here to say that all the large Rock Crystal for which Brazil has been famous was found to be modified quartzite and not a phase of pegmatite nor granite as was previously supposed. In all the cases examined by the writer the bedding planes were more or less horizontal but the crystal planes were vertical. Often the crystals were clear only in the bedding planes and were quite obscure and sandy-looking between the bedding planes. Several small hand specimens were brought back, one of the best of which is now in the British Museum at South Kensington, but as all travelling in that region was done on horseback, and the writer travelled far and fast, there was a decided limit to the amount of specimens it was possible to carry. Curiously enough, when some of those crystals were cut into thin section longitudinally they showed complete unification of the crystal, even in those parts between the bedding planes which looked gritty to the naked eye. On a large scale in the field, however, the transition from a gritty quartzite to clear crystal could be traced. When the sections were examined in polarized light under the microscope fine grains of mica were occasionally seen even in the clear parts of the crystal.

Closely associated with these recrystallized quartzites are the sericitic and talcose schists in which on the high plateau the diamonds are found. In the districts of Sopa, Guinda, and Boa Vista round Diamantina which the writer studied, these schists were not interbedded with the quartzites but formed lodes or pipes rising more or less vertically through the quartzites. Mining has not been

carried deep in these situations, however, and indeed they are not generally recognized as pipes (2). The weathered schist and talc which is exposed is very different from the hard green kimberlite of the South African pipes, but the field characteristics are very similar. Several of the pipes round Diamantina are traversed by streams which combine to form the Jequitinonha River and the gravels of these streams are all diamond-bearing. Local miners have learned from experience that certain streams contain diamond-bearing gravels and others flowing from the same district do not. The present writer would not dare to make emphatic assertions on this point, but in the few cases which he was able to examine, those streams which were said to be devoid of diamonds also showed no signs of schist nor of the fine white clay to which it turned in the river bed. It seems almost conclusive evidence, therefore, that this schist found in the lodes or pipes coming through the quartzites should be the original home of the diamond which is now found in river gravels hundreds of miles away or embedded in later sedimentary rocks.

In the neighbourhood of the schistose diamond-bearing pipes another modification of the quartzite was noticed. This was most evident round the margins of the pipes or on the water courses below the pipes where there was a considerable amount of white talcose clay with the quartzites. Very often thin vertical sheafs of more coherent material could be seen running through the beds which stood out as marked ribs where the rock was weathering away. The rock was often so soft and rotten that it could be scraped away with a stick and the thin sheafs extracted. These were very flexible when wet. These flexible sheafs are the itacolumite of Humboldt, but the term is often extended to include the whole schistose quartzite in which they occur. It is again a significant fact that in all cases which the writer noted, the sheafs were vertical and ran across the bedding planes, although it must be mentioned that had they been parallel with the bedding planes they would not have been so conspicuous, and so passed over more easily in a cursory examination.

Gold is also found on the Serra do Espinhaco and was extensively worked in the neighbourhood of Diamantina before diamonds were discovered. But the gold is found in ordinary veins of white or rose-coloured quartz which pierce the quartzite in all directions. Some of these veins are only 2 or 3 inches across and they have been worked by cutting deep, narrow clefts into the quartzites and extracting the vein quartz for crushing and washing in the streams. But the labour of cutting the quartzites thus is very great and operations have stopped when the cutting was only a few feet deep. But these clefts may still be seen following the veins of quartz wherever they crop out. It should be noted at once, therefore, that although gold and diamonds are found often within a few miles of each other, and both in the Archæan quartzites, yet their mode of occurrence

is widely different, the gold being found in vein quartz and the diamonds in a pipe or lode of sericitic schist and metamorphic rock. Most of the "mines" of the district, however, are placer mines in the extensive river valleys, and in these, naturally, the gold and diamonds may be worked together along with other precious stones such as topaz, beryl, aquamarine, tourmaline, and clear and coloured varieties of rock crystal. For hundreds of years now immense harvests of gold, diamonds, and precious stones have been taken from the gravel beds of the great rivers which have their origin in the high plateau of Brazil, yet comparatively little effort has been made to find the original home of the diamond. This is due of course to the ease with which placer mines can be worked compared with the labour of cutting and mining in the hard quartzites of the higher regions. But when hydro-electric power is more generally developed in the country and trained geologists are employed by the various mining companies, the various diamond "pipes" of Brazil will probably become located and as well known as those of South Africa.

On its eastern side the Serra do Espinhaco slopes off gradually to the Atlantic Ocean and the granite and gneiss are exposed again under the quartzite cap. On its western side, however, the Serra do Espinhaco shows a steep escarpment down to a lower plateau composed of limestones and shales. This lower plateau lies between 2,000 and 3,000 feet above sea-level and is really a wide and shallow river valley drained by the Rio das Velhas. The limestones are often massive like dolomite and the rocks of this lower plateau are assumed to be of Permian age. Still farther west beyond the valley of the Rio das Velhas the granites and gneiss appear, rising again to form a higher plateau. The granite and gneiss is often capped by quartzites, but here they are generally impregnated with iron ores and are of the varieties known by the collective name itabirite (5). The name Serra do Canastro (6) has been applied to this higher region of granite and gneisses capped by quartzites and itabirites, although here again the name Serra is a misnomer as the country is really a rolling plateau. The name Serra do Canastro is not found in modern geographical literature, but from considerations of geological structure, geographical contour, and watershed it seems advisable to introduce it again.

The State of Sao Paulo lying south of Goyaz and west of the high plateau proper is covered by soft reddish sandstones of Triassic age traversed by great belts of igneous rock including nepheline-syenite, jacupirangite, and diabase. These rocks have all weathered considerably and covered the ground with a heavy red soil. Sao Paulo is essentially an agricultural State.

The writer has purposely omitted from the small scale map which accompanies this article the numerous intrusions of igneous rock found all over the high plateau, and probably all of Palæozoic age. As the literature on this subject is very extensive already and the writer has nothing new to add, they are better omitted at present

from this brief summary. The boundary of the various geological horizons shown on the map are also only approximate.

The only essential difference between this map and that magnificent geological map of the whole of Brazil published by Dr. Branner (3) is that in the latter the granite and gneiss is shown bordering the Permian limestones along the edge of the Serra do Espinhaco, and the quartzites are shown as a comparatively insignificant outlier some distance away. Where the writer examined the western escarpment of the Serra do Espinhaco no granite or gneiss was visible. The quartzites capped the ridge, which was very steep and covered by screes and heavy soil. The writer is not prepared to assert that the quartzites abut on the limestones throughout the whole length of the ridge, but according to his interpretation the hard quartzites acted as a protective cap to the granite and gneiss and formed a cliff against which the seas beat in Permian times when the limestones and muds were being deposited below.

The outstanding feature of the geology of this region is that the highest part of the high plateau from which rivers radiate out to the north, south, east, and west is composed of Archæan rocks. Later rocks appear in more or less regular succession on the flanks of the plateau towards the north and west. The plateau averages 5,000 feet along the ridge of the Serra do Espinhaco and 3,000 to 4,000 feet in Goyaz. Between these two districts it averages between 2,000 and 3,000 feet and it is on this lower level that we find the Permian limestones and shales. According to other observers the Permian rocks continue northward until they in turn are covered by more recent deposits (4). Evidently, therefore, during Permian and possibly more recent times the sea has invaded these depressions in the plateau from the north. As the sea receded again these areas were drained by mighty rivers which persist in their original courses with one or two curious exceptions to the present day. In the valleys many writers have described rocks of Tertiary and Quaternary age though they are as a rule much too small in area to be marked on a geological map. Special mention might be made of the Tertiary lake deposits in the broad valley of the Parahyba.

The foregoing notes are sufficiently strong to establish the assumption that the high plateau in its present form is a very ancient land surface, persisting in fact from the earliest Palæozoic times. When we consider the great age of the rocks, and the great denudation which they suffer, the conclusion is forced upon us that the high plateau is a region which has been steadily rising throughout great geological ages, and this process of uplift may be still going on. It has risen vertically as a whole and not by a system of buckling of the crust. The quartzites which cap the crust are still very regularly and horizontally bedded. The system of thrust faults by which the Archæan sediments are let down locally into the gneiss at Lafayette is very ancient, probably Archæan, and has no bearing on

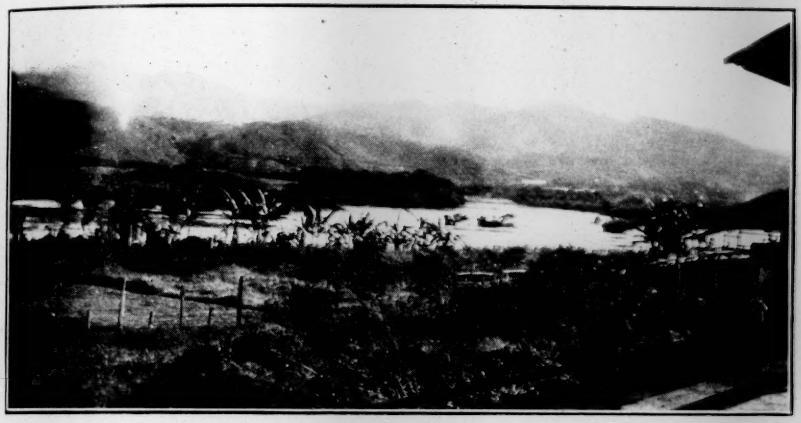

FIG. 1.—THE VALLEY OF THE RIO PARAHYBA, AND THE SERRA DA MANTIQUEIRA.

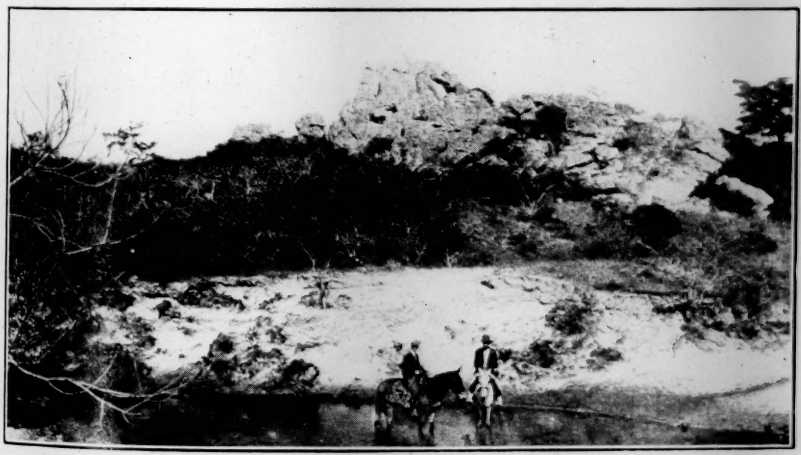

FIG. 2.—IN THE QUARTZITE COUNTRY OF THE SERRA DO ESPINHACO.

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the general uplift of the whole plateau. The south-east boundary of the uprising area is a fault-line which coincides with the south-east coast and the marginal fracture line of the Atlantic basin. The uplift is greatest along this line—the Serra do Mar—and gradually decreases towards the north and west, giving long and gentle slopes in these directions.

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The Oil Horizons of England.

By C. E. N. BROMEHEAD, B.A., F.G.S.

INTRODUCTORY.

DURING part of 1918 the writer investigated the Cannel Coal and other possible sources of oil, together with occurrences of free Petroleum in the Yorkshire, Durham, and Northumberland coalfields, and subsequently watched the Government borings for oil in Derbyshire. The main results of this work have already appeared in sundry Geological Survey Memoirs, but some general conclusions on the subject of Petroleum in England and the facts which suggested them are here put forward. The possible oil-bearing horizons are regarded as three in number: the Lower Carboniferous rocks of Derbyshire, the Coal Measures in various fields, and the Upper Jurassic or Lower Cretaceous strata of a part of the Sussex Weald. Before giving details, a few remarks on Petroleum in general are necessary.

Petroleum is defined by Sir Boverton Redwood as including "all hydrocarbons, whether gaseous, liquid, or solid, occurring in nature".[1] For the present purpose we are concerned mainly with the liquid forms, the gaseous and solid being important in so far as they give evidence of the existence, now or in the past, of liquid Petroleum in their near neighbourhood. Liquid Petroleum, or Oil, is commonly divided into two main groups, the members of the first having a paraffin base and those of the second an asphaltic base. It is unnecessary to enter into chemical details, but it may be noted that, on the whole, paraffin oils are of a lighter colour and gravity and lower sulphur content than asphaltic oils, that they

[1] For references see Bibliography at end of paper.

are indigenous to shales rather than limestones, and of a vegetable rather than an animal origin; for instance, a Pennsylvanian oil derived from shale gives specific gravity ·801, sulphur 0·06 per cent (Beeby Thompson 2), while three analyses of an asphaltic oil from the Tamaso Limestone in Mexico give specific gravity ·94 to ·99, sulphur 1·93 to 4·81 per cent (Stewart). A typical shale oil is that of Southern California, indigenous to the diatomaceous Monterey Shale, though now obtained from sandstone reservoirs adjacent to the shale either through faulting, conformable sequence, or unconformable deposition (Clapp).

Oil can only be obtained in quantity from a porous rock such as a coarse sandstone or a limestone, the latter preferably dolomitized. In the Upper Carboniferous Rocks of England the porosity of the Millstone Grit has been determined as 18·2 per cent for a coarse and 13 per cent for a fine-grained sample, that of the Carboniferous Limestone as 2·25 per cent for a normal and 9·5 for a dolomitized bed (Moore). When the oil has reached a porous rock the anticlinal theory of accumulation may usually be applied, but it is important to ask how an oil indigenous to a shale reaches such a reservoir. Shale is an argillaceous, and therefore an impervious, rock, but it is laminated parallel to the bedding. The amount of percolation through the beds is negligible, and a shale frequently forms the cap-rock above an oil-sand, but along the bedding capillary movement may take place. If such movement will anywhere lead to a porous rock, that rock may become an oil-sand; in other words, accumulation can only take place when a suitable rock is brought into angular contact with the parent shale. In the Coalinga district of California where the oil is indigenous to diatomaceous and foraminiferal shales of the Tejon (Eocene), the yield of the overlying Miocene Sandstones is stated to depend on the degree of unconformity between these formations. Where sandstones cut obliquely across the shales good yields are obtained; where, on the contrary, the beds approach apparent conformity little oil is found (Arnold and Anderson). At Los Angeles in the western part of this field the same effect is partly due to faulting, many successful wells being located along an important fault (Bosworth). The same principle applies also to the San Joaquin fields (Pack). Similarly, in Roumania a petroleum is nowhere found in commercial quantities in the Salifère, although it everywhere contains oil, but wherever suitable beds of later age unconformably overlie or recline against the Salifère the former contain oil, often in enormous quantities, and the yield "bears a very definite relationship to the structure and angle of unconformity" (Beeby Thompson 1). In this field faults are also of great importance in facilitating accumulation. The same writer states that "in the Bibi-Eibat field of Baku a number of important faults have been located, and they have been found to exercise a distinct influence on the production of the wells. A series of

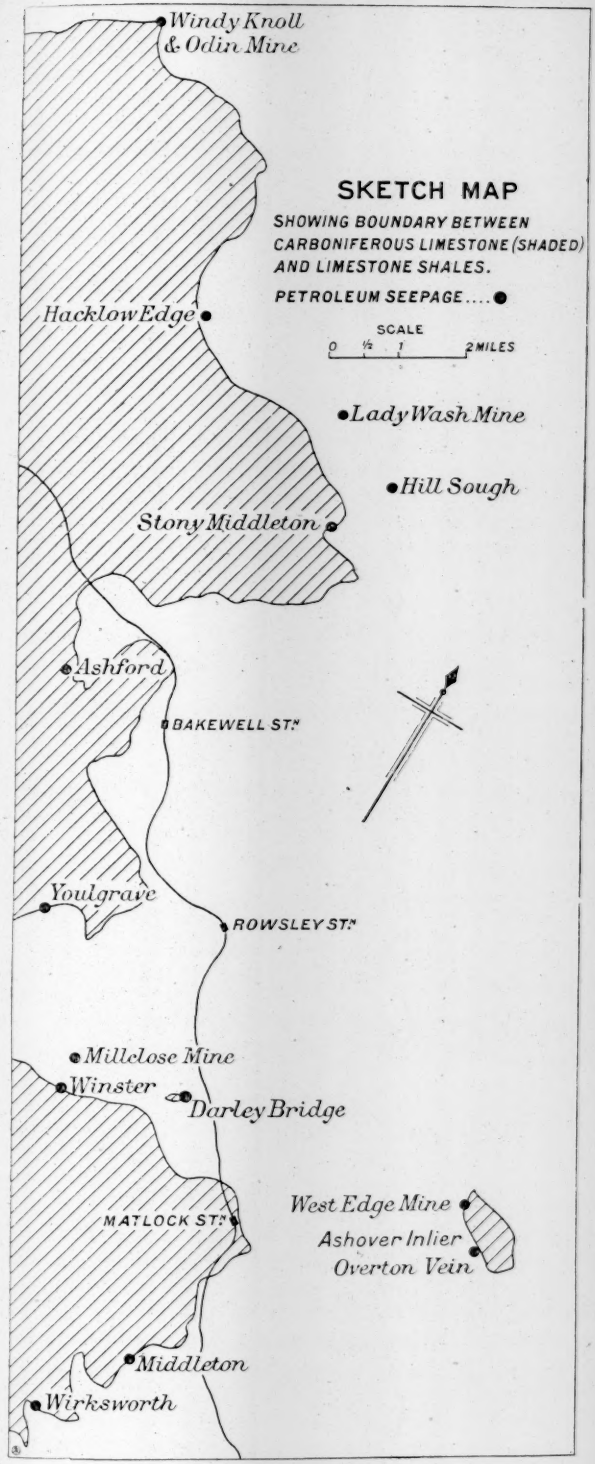

FIG. 1.—Geological map of part of Derbyshire showing petroleum seepages.

exceptionally large flowing wells was ascertained to lie along a fault, which they struck at a considerable depth. In Mexico, igneous intrusions form a barrier against migration along the bedding planes and shatter the rock in their immediate vicinity, thus providing access to the reservoir rock (Villarello). This question of the means of access from the parent-rock to the reservoir has been emphasized because it has hardly received the attention it deserves in the literature of oil-geology in general and because it will be shown below to be of importance in England.

The Oil Horizons of England.

(1) *The Lower Carboniferous Rocks of Derbyshire.*

The best-known occurrence of Petroleum is near Castleton, at Windy Knoll. Here a bright yellow tar exudes from the limestone

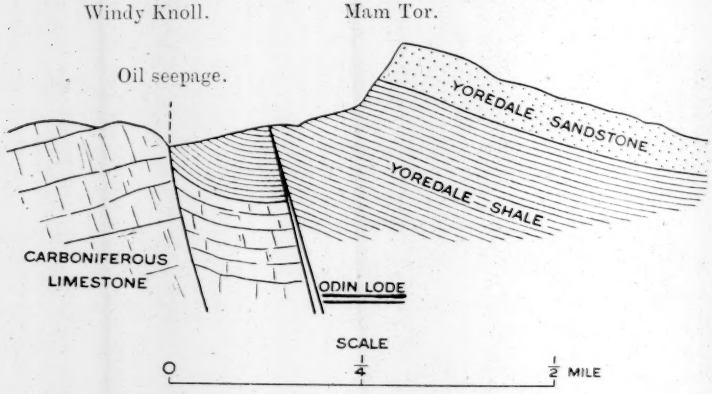

Fig. 2.—Section through Windy Knoll and Mam Tor.

at the top of a small quarry; it is stated that the flow occurs "after rains in summer" (Dalton). On exposure the colour changes to a deep brown, and the texture to an elastic solid forming the mineral known as Elaterite, or Elastic Bitumen, first described from this locality (Lester). Two specimens of this material were analysed by Macadam with the following result:—

	Per cent.	
Carbon . .	83·62	82·80
Hydrogen . .	11·19	11·92
Oxygen . .	4·78	4·92
Nitrogen . .	0·17	0·11
Sulphur . .	0·24	0·25

The proportion of oxygen and the relative proportions of carbon and hydrogen show that there has been considerable oxidation and loss of water in an original paraffin material. It may be noted that the percentage of sulphur present is approximately the same as in the Hardstoft oil. A further stage in the inspissation of the material results in a hard lustrous bitumen found in cavities in

the limestone and the accompanying veins. The same material is also found close at hand in the Odin Mine; here the bitumen is abundant in cavities in the lode and large masses of elaterite have been found, while the liquid form is indicated by the occurrence of stalactites of bitumen found in the levels. The Odin lode is the infilling of a fault along which the Limestone Shales are brought down against the limestone, while a parallel fault with the same effect runs through Windy Knoll (see Fig. 2). No occurrences of elaterite or bitumen of magnitude comparable with that described above have been recorded in the mass of the limestone. It is suggested that the petroleum is derived from the shale, and that it seeps along the bedding planes till it reaches the faults, when the cracks and cavities in the limestone afford opportunity for its accumulation.

The occurrence of liquid Petroleum in the Yoredale Shales and in the veins near or under these shales has been noticed for many years. In 1734 Short described the oil or wax found in "a stratum of Boulder Stones about two fathoms above the lead ore" at Hacklow Edge vein. From his account, and from comparison with the occurrence at Ashover mentioned below, it would appear that the "stratum of boulder stones" is a line of geodes in the shale. Oil is also recorded from Stony Middleton, Stoke Sough, the Mag Clough level at Lady Wash Mine, Black Marble Quarries at Ashford, and, accompanied by gas, at Hill Car Sough near Youlgrave (N. Derbyshire Memoir). Dr. J. L. Fletcher, Medical Officer for the Matlock District, in a letter to the author, says that at Darby Bridge oil has been noticed on the surface of the water in old wells sunk through the shale; he mentions similar occurrences at Winster, where petroleum was also found in the shale at the Limekiln Mine. Near Middleton the Gang Mine, on the eastern part of the Gang vein, worked lead ores in the shale and obtained some petroleum. The Good Luck Mine at Wirksworth struck a hot spring and also found petroleum in the shale. At the Ashover Inlier oil was found in geodes in the shale when mining the West Edge vein, which closely follows the boundary of the shales and the limestone (*Oil News* and Sheet Memoir 112).

The above instances are given roughly from north to south; the majority of the oil is known to be derived from the shales; those where it was found in the limestone lie, as may be seen from a glance at the map (Fig. 1), close to the boundary of the shale. Many observers have recorded the occurrence of drops of oil or specks of dried-up bitumen in the limestone in the cavities of brachiopods or corals. In the case of the latter, it is chiefly in the more dolomitic limestones that the spaces between the tissues are hollow and contain specks of bitumen (Sheet Memoir 112). Of the brachiopods those in which oil or bitumen has been found are for the most part gigantid *Producti*, which form beds near the top of the limestone. In both cases it would appear that the

limestone contains Petroleum at the top only when hollows suitable to contain it are present. This distribution again suggests that the oil is derived from the overlying beds and that the limestone locally functions as a reservoir. Similar occurrences of bitumen or oil in the pores of dolomitized limestone are known in Mexico, but Jeffreys and Garfias agree that this constitutes no evidence that the oil is indigenous to that rock.

In the Millstone Grit there is only one important occurrence of Petroleum, that of Kelham. Here a boring was put down to prove the Coal Measures in 1908–12. The Millstone Grit was met with at a depth of 2,354 ft., and found to consist of sandstones and shales of the usual type; the thickness, however, was at most 148 ft., below which were shales, crowstones, and fossiliferous earthy limestones characteristic of the lower part of the Carboniferous Limestone Shales. A description of the section has been given by Dr. Gibson (Summary, 1917), who remarks that "it is necessary to infer that the boring passed through at least one fault". Oil was first obtained on 21st August, 1911, in a grit extending from 2,437 to 2,452 ft., underlain by shales described by Dr. Forbes Leslie as "waxy". A flow of 5 to 8 gallons per day was noted, although the boring was full of water. The presence of the oil here cannot be accounted for on the anticlinal theory; as Dr. Leslie remarks, "the Kelham boring is not near any well defined axis [as far as is known], but the anomalous sequence of beds. . . . may have some structural cause, with which the discharge of oil is connected." "The character of the oil was examined by several eminent chemists, and reported to be undoubtedly a true petroleum of paraffin base, dark reddish-brown in colour by transmitted light, of a not unpleasant odour, moderately high viscosity, and a specific gravity of 0·915 at 60° Fahr. Its flash point was 146° Fahr. (close test). It yields no benzine and only a commercially unimportant quantity of kerosene, but the content of solid hydrocarbons is unusually high, 7 to 8 per cent of hard and soft paraffin wax, according to melting point. The sulphur present amounts to 0·95 per cent" (*Oil News*). The high percentage of solid paraffin rather suggests a Coal Measure origin (see below), but there is not sufficient evidence to settle the point. Further borings in search of this oil put down by Oilfields of England, Ltd., have not yet met with success.

It is well known that the Government borings put down to test the Lower Carboniferous rocks of Derbyshire met with considerable success at Hardstoft. Oil was struck on 3rd June, 1919, at a depth of 3,077 ft. The oil overflowed at the rate of about one ton per day, and is still (1923) flowing, though at a less rate; it is of paraffin base, specific gravity ·823, and contains 0·26 per cent sulphur. The commercial products obtainable are given as Motor Spirit 7·5, Kerosene 39, Gas Oil 20, Lubricating Oil 30·5, Paraffin Wax 3 per cent. Further details of the examination by Mr. Hackford

are given in the *Mineral Oil Memoir*. The character is that of a shale oil similar to that found at Windy Knoll. The samples of rock from the oil horizon are a mixture of limestone and shale; these, together with the structure of the Coal Measures at the site, indicate the presence of a fault bringing the Limestone Shales against the Limestone, as shown in Dr. Gibson's section (Fig. 3).

The conclusion from the above data is that the oil found in the Lower Carboniferous rocks of Derbyshire is indigenous to the lower part of the Limestone Shales, which are black in colour and of an "oily" appearance, and occasionally show little veins of black bitumen along the bedding. Were the oil indigenous to the limestone, its character would be different, and the dome-like structures which bring that rock to the surface at Ashover and

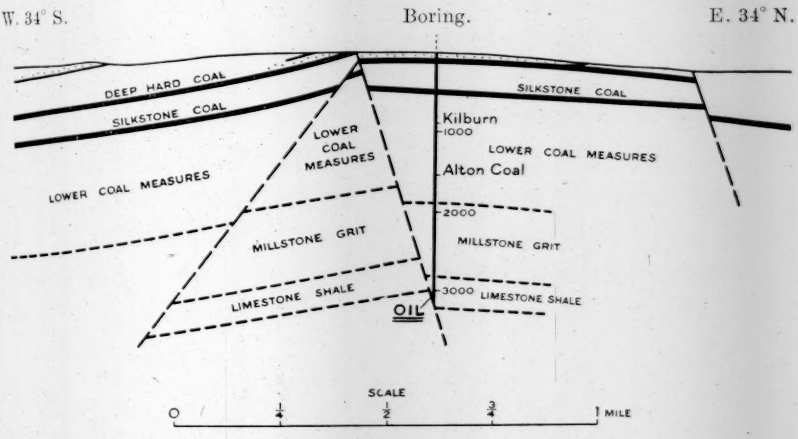

FIG. 3.—Horizontal section through boring Hardstoft No. 1.

Crich, and again at Astbury in Staffordshire, should have had much oil concentrated in them. Since these limestone inliers can only have been exposed to weathering in comparatively recent times, there should be obvious signs of the impregnation by petroleum remaining, which is not the case.

Beds of Yoredale age have yielded oil in other parts of the country, e.g. in a boring at Norton, County Durham, "petroleum welled up continuously as a black liquid from Yoredale rocks consisting of alternations of dark shales and sandstones: it was followed by large amounts of hydrogen sulphide" (Tate). A considerable amount of gas has been found in the neighbourhood at various times, but there is little evidence to suggest the presence of oil in quantity: it is possible that the petroleum, both gas and inspissated oil, is derived from the neighbouring Coal Measures, not from the Yoredale rocks, its escape from parent shales being facilitated by unconformable overlap.

(2) *The Coal Measures.*

From the Coal Measures petroleum has frequently been obtained in practically every coalfield. In the Survey Memoir on Mineral Oil, etc., 17 instances are mentioned; the author has obtained further information concerning some of these and added five more; in addition to these, petroleum is stated by Prestwich to be abundant in the Coalbrookdale field. Out of the total of 22, 2 are from borings; of the remaining 20 the petroleum is known to have been connected with faults in 12 cases, and several of the faults are definitely stated to bring shales against sandstones. The character is known in 14 cases—the petroleum is either a solid paraffin wax or a viscous mixture of paraffin having on exposure the consistency of vaseline at normal temperatures. The colour is dark reddish-brown with a greenish fluorescence by reflected light. The sulphur content, when known, is low. It is unnecessary to give a complete list of the occurrences known to the author; descriptions may be given of a few that are of importance either on account of the large amount obtained or of the fullness of the information available.

At Riddings Colliery, Derbyshire (*Mineral Oil Memoir*), the amount obtained from the earlier seep was 300 gallons per day for two years; this flow had not entirely ceased when the second was met with in 1873, amounting to 300 gallons per week for eighteen months; it exuded from the roof of the gallery adjacent to a fault having a throw of 20 ft. (Cadell and Marshall). The specimen in the Geological Museum examined by the writer is of the consistency of vaseline and evidently contains a large percentage of the higher paraffins and is a typical Coal Measure oil; it cannot therefore be regarded as having come from the Limestone Shales by the great Riddings Fault; it was for paraffin-wax that Young worked the first flow; the second was used as wheel-grease or lubricant.

The only instance where the author has been able to examine a Coal Measure seep in situ is at Manvers Main Colliery, Yorkshire; he has given a full account in the Memoirs referred to. Here again the amount was considerable, sufficient to be worth collecting for fourteen years. The oil came from small faults bringing shale against sandstone, and was characterized by the large proportion of solid paraffins. A lump of solid hatchettine 15 inches across was found (Cohen).

At the Clowne Colliery, near Chesterfield, oil was found in 1884; some of it was used at the colliery, but 10,000 gallons were sent away for distillation before a fire, in 1887, put a stop to operations; it was a paraffin oil and yielded wax and lubricating oil in addition to lighter fractions (Radley).

At Hemsworth Colliery, 8 miles south-west of Wakefield, oil was found in the roof of the Haigh Moor seam in 1908, and again in 1911. In the latter case the seepage was on a fault with a throw of 11 ft., but no petroleum occurred where the same fault cut the Barnsley seam. The oil was yellow as it ran, but turned dark

brown on exposure. It was examined chemically and found to contain the paraffin eikosane ($C_{20}H_{42}$), and other members of the series having the formulæ $C_{22}H_{46}$, $C_{23}H_{48}$, $C_{24}H_{48}$, $C_{24}H_{50}$, $C_{25}H_{28}$, $C_{26}H_{54}$ and $C_{32}H_{66}$ (Cohen).

A petroleum from the roof of the Cockshead seam in North Staffordshire (probably from Mossfield Colliery, Longton), has been examined chemically by Mr. A. A. Hall. He describes it as dark brown in colour, but dirty green by reflected light. It was solid at 15° C., and crystals began to separate out at a temperature of 18°. Approximate analysis showed volatile matter 98·25 per cent, fixed carbon 1·71, ash 0·03. The sulphur, determined by Barratt and Lomax's method, was 0·62 per cent. The oil was a mixture of paraffins, mostly those of high molecular weight, with some olefines and possibly some napthenes and phenolic bodies.

Wax from Garswood Hall, Lancashire, proved to be pure pentacontane, $C_{50}H_{102}$ (Sinnatt); of that from Ladysmith Mine, Cumberland, Bedson says "it would appear that the lowest member of the paraffin series present is $C_{10}H_{22}$, whilst . . . . it is evident that a hydrocarbon $C_{24}H_{50}$ may be present.

Whether the Coal Measure petroleum is definitely associated with coal seams is doubtful. In most of the known instances the oil is said to drop from the roof of the seam, but it does not necessarily follow that it occurs more frequently in that position. There are many miles of workings in the coal seams, but the intermediate measures are comparatively rarely cut through except in shafts, while small quantities of oil in the floor of the workings would easily escape notice. In South Yorkshire and Nottinghamshire, however, traces of oil are frequently found in the Barnsley Rock, a bed of sandstone sometimes partly replaced by shale overlying the Barnsley Seam; the miners engaged in sinking shafts regard the oil as a means of identifying that stratum.

From the evidence given above certain general inferences may be drawn: (1) Petroleum is of frequent occurrence in Coal Measures and is sometimes in sufficient quantity to be of commercial value. It would not be worth while to search for it, but any found in colliery operations should be collected; in some cases galleries might be cut to increase the flow, as at Pechelbronn. (2) The petroleum is essentially a mixture of paraffins in which the high members of the series predominate; consequently it is viscid or semi-solid on exposure at ordinary temperatures; the sulphur content is low. (3) From the character and from several instances it is inferred that the petroleum is indigenous to shales. (4) As in the case of the Lower Carboniferous oil, it is only found in noticeable quantities where a porous sandstone is faulted against the shale. In exceptional cases the same effect may be produced by unconformable overlap, e.g. the traces of petroleum in the Pre-Cambrian rocks of Pitchford, Salop, are probably derived from Coal Measures now denuded away.

(3) *Sussex.*

Natural gas has been known to exist in the Heathfield district of Sussex since 1836, and has been used since 1899; a full account, with references to previous literature is given in the Mineral Oil, etc., Memoir. The most satisfactory analysis shows over 93 per cent methane and slightly less than 3 per cent ethane; J. E. G. Harris has recently found 0·21 per cent of helium. The gas is therefore a true petroleum of the "dry" type. It must be an emanation from a liquid petroleum or oil; but it by no means follows that such oil exists now or could be obtained by drilling. Gas occurs in all oilfields and frequently occupies the highest points in a structure in which oil is found in intermediate positions and water below. But such gas is of the "wet" type; the dry gas of the Canadian fields seems to be a relic of an oil of which little now remains except heavy residues. The opinion that the Sussex oilfield is a "has-been" or thing of the past has been put forward by Mr. Cunningham Craig. More recently Mr. H. B. Milner has given reasons for thinking that the parent-rock is the Kimmeridge Clay and the chief gas-reservoir the overlying Portland Sands. The writer has nothing to add to these views beyond recording his agreement; they are only referred to here for the sake of completeness.

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The Occurrence of Detrital Barytes in the Permian Basal Sand at Nitticarhill.

By H. P. Lewis, B.A., F.G.S.

THE Permian Basal Sands in South Yorkshire and North-East Derbyshire are very inconstant in thickness and they are often absent or unexposed over wide areas. They evidently filled eroded hollows in the Carboniferous floor and it is interesting to note that they are usually best developed where the underlying Coal Measures are soft and essentially shaly in composition. In the region under discussion some sections show the Lower Permian Limestone resting directly on the basal sand with but a slightly arenaceous base. Such is the case at the well-exposed sections east of Frickley, 15 miles north-east of Sheffield and at Harthill, 10 miles south-east of Sheffield.

In an old sand pit at Nitticarhill, 1 mile south of the Harthill section, the "Marl Slate" overlies the Basal Sand and the junction is well exposed. Neither the top of the marl nor the base of the sand can now be seen. From this locality a few excellent specimens

of *Productus horridus* Sow. have been obtained from the Marl Slate, which here consists of alternating layers of calcareous shale and marl. The marl contains curiously shaped concretions irregularly distributed throughout its lower portion and especially massed at the junction with the underlying sand. These concretions prove to be almost entirely calcareous and they are formed of crystalline growths of calcite. They appear to have been in part re-dissolved and the hard calcareous sandstone, varying from 2 feet to 6 inches in thickness traced in the direction of dip for 50 yards, and found at the junction with the marl, probably owes its cementation to a solution containing carbonates derived from the marl series. The upper portion of the sandstone forms a hard, tough rock 4 to 6 inches thick, and resting on it are the majority of the concretions mentioned above. These in section often resemble the links of a chain and their average dimensions are $1\frac{1}{2}$ by $\frac{3}{4}$ inches; they differ from those found less regularly distributed higher up in the marl by their smaller size and less branching forms. In the uppermost thin band of hard sandstone, which has resisted weathering and is therefore somewhat undercut, detrital barytes has been found.

In slices of the sandstone some of the grains are seen to be of barytes, similar in clearness, shape, general size and birefringence to the grains of quartz. The barytes is, however, distinguishable from quartz by its higher refractive index, while some grains, though not all, show cracks following the prismatic cleavage and, in others, basal cleavage cracks alone are apparent. In a few grains regularly interspaced wavy lines, emphasized by the inclusion of a dark-coloured impurity, were noticed. This phenomenon, together with the production of strain shadows, may be due to distortion produced during the preparation of the slice, and barytes grains showing strain shadows and kindred phenomena may easily be mistaken for strained and shattered quartz. Occasionally the cleavage cracks are filled with a chloritic mineral showing that the opening of these cracks may not be wholly the result of slice preparation but may have been completed prior to the incorporation of the grains in the sand. The barytes grains are variously angular, subangular or rounded. Where cleavage cracks are evident it can be seen that pieces have torn away during transport, more or less parallel to the cleavage, leaving the grain with an uneven outline (see Fig. 1). The detrital nature of the barytes is further demonstrated by the general clearness of the grains as distinct from the somewhat iron-stained cement. The grains in no way resemble the discs of barytes occurring in the "Shales with Beef" at Charmouth and thought by Mr. Richardson to be more probably secondary segregations rather than contemporaneous and the equivalent of the barytes nodules dredged from recent seas.[1] Most of the grains are over 0·4 mm. in diameter, but they rarely exceed 1·0 mm. Minute angular grains having a longest

[1] *Q.J.G.S.*, vol. lxxix, 1923, p. 88.

diameter of 0·05 mm., and which may be the chippings of the larger grains, are also present.

The cementing material is of special interest. It is in part calcareous and in part barytes. Enclosed within it occur minute rhombs of dolomite sharply angular and varying in size from 0·05 mm. to 0·01 mm. as measured along the longer axis. Owing to their higher refractive index these rhombs stand out in good relief from the enclosing barytes and their birefringence also distinguishes them from the latter mineral. Where the enclosing mineral is calcite their relief is by no means so pronounced. Some of the rhombs are iron-stained. From the irregular manner in which the rhombs are distributed in the cement, occurring sometimes as single isolated crystals and in other places as crowded aggregates, their sharp

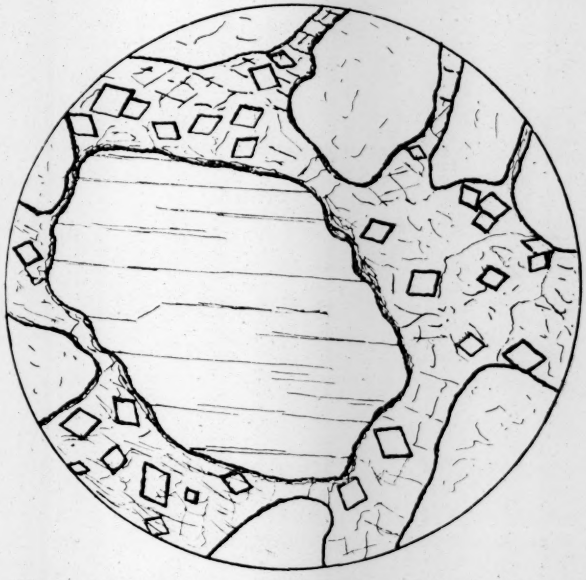

Fig. 1.—Nitticarhill sandstone. Slice showing a large barytes grain in a cement enclosing dolomite rhombs. × 60.

outlines and the fact that they are frequently more heavily iron-stained than the enclosing cement, it is thought that they were precipitated as minute crystals prior to the precipitation of the calcite and barytes cement. Moreover, in the same section at Nitticarhill and at other localities from which samples have been collected, where the Lower Permian Sands are incoherent, such dolomite rhombs are common among the fine-grained constituents of the deposit. Their presence may be taken to indicate the oncoming of arid conditions. Much of the Magnesian Limestone itself, in South Yorkshire at all events, is built up of dolomite rhombs of small size, and shows

many of the features which are usually associated with the deposition of a sandstone, current bedding among others. Similar minute dolomite rhombs have already been recorded from the Keuper Marl of Leicestershire by Dr. Bosworth,[1] and by Dr. Cullis in the Trias Marls of Gloucestershire.[2]

In the Nitticarhill sandstone there is no instance of a dolomite rhomb being enclosed in the detrital barytes, the rhombs being always confined to the cement. Occasionally the rhombs are seen to be enclosed in a barytes cement which is in crystalline continuity with part of a barytes detrital grain. The following account of the

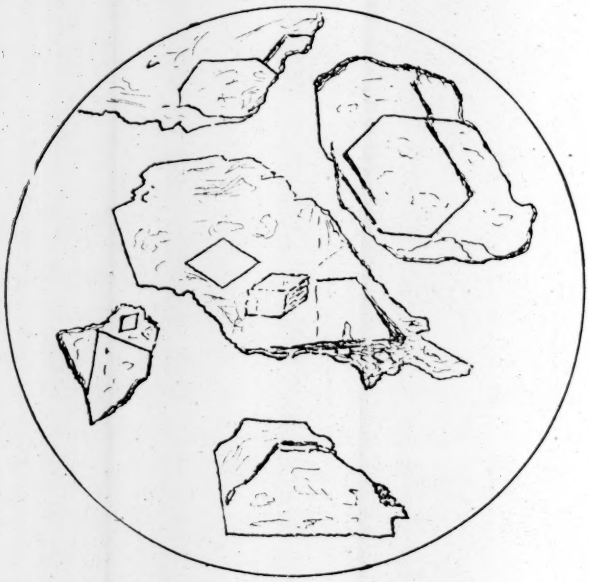

FIG. 2.—Nitticarhill sandstone. Barytes cleavage flakes from the cement separated after crushing and treating the sandstone with HCl. A negative crystal, rhombohedral in shape, left after the removal of the dolomite, is shown in the centre of the field. × 60.

possible sequence of events during the cementation of the sandstone may explain its structure. Percolating waters, if they descended from the Marl "Slate" above, undoubtedly would be already saturated with carbonate and there would therefore be no tendency for the dolomite rhombs in the sandstone to be dissolved in the descending solution. The detrital barytes, on the other hand, to some extent might become dissolved in the carbonate solution and later, on change of temperature, be redeposited together with the calcite, as a cement, enclosing the pre-precipitated rhombs of dolomite.

[1] *Q.J.G.S.*, vol. lxviii, 1912, p. 287.
[2] *Rep. Brit. Assoc.*, 1907, p. 506.

The nature and relationship of the barytes and dolomite were further investigated. A lump of the sandstone was treated, without crushing, with dilute, followed by hot concentrated hydrochloric acid. By this treatment the main mass of the cement, which was calcareous, was removed. The portions cemented by barytes remained as compound grains, which formed the bulk of the heavy residue after separation in bromoform.

Another piece of the rock was crushed and the heavy minerals examined. Cleavage flakes of barytes from the cement contained well-defined rhombs of dolomite, which had a sort of poecilitic or ophitic arrangement in the barytes, but no regular crystallographic relation to the axes of the latter mineral was observed. A second crushed sample was treated with acid and in some of the barytes fragments of the heavy crop were negative crystals of rhombohedral shape left where the dolomite had been removed (see Fig. 2). As the majority of the barytes flakes lay on the basal pinacoid, the main cleavage, the dominant angles observed were those between the prismatic cleavage breaks, or between the prisms and (010) which exceptionally presented a rather imperfect cleavage break. The well-marked relief and low birefringence were characteristic.

I am indebted to Mr. W. J. Rees, B.Sc., F.I.C., for the following bulk analysis of a typical specimen of the sandstone.

SiO_2 . .	62·23
Al_2O_3 . .	1·29
Fe_2O_3 . .	1·43
$CaCO_3$ . .	20·52
$MgCO_3$ . .	5·17
$BaSO_4$ . .	8·54
	99·18

It is well known that whereas barytes (more rarely celestine) often occurs as the cementing material in sandstone,[1] detrital barytes rarely persists in sands owing to its softness and good cleavage, which cause the mineral to be broken up easily during transport. The presence of detrital barytes in the Permian Basal Sands of North-East Derbyshire, therefore, indicates that the source of these sands was not far from their present position. In attempting to trace the source of the sands some knowledge of the other heavy minerals which accompany the barytes is necessary. With this end in view these minerals were studied some months ago from samples collected from sections within a few miles of Sheffield. Except for tables in books devoted wholly, or in part, to sedimentary petrology,[2] no account has appeared to my knowledge describing these minerals. A brief allusion to them here needs therefore no apology. They include the following:—

[1] H. H. Thomas, "Petrography of the New Red Sandstone": *Q.J.G.S.*, vol. lxv, 1909, p. 234; W. W. Watts, "On a Keuper Sandstone cemented by Barium Sulphate": GEOL. MAG., 1894, p. 510.

[2] e.g. H. B. Milner, *An Introduction to Sedimentary Petrography* and A. Holmes, *Petrographic Methods*.

Garnet.—This is ever very abundant and occurs as angular or rounded grains, brown, pink or colourless. Many of the grains are large, some show dodecahedral cleavage and others quartz inclusions.

Zircon.—Prisms and rounded grains of this mineral are abundant. The prisms are usually well-shaped and the crystals are often terminated by a combination of the pyramids (311) and (111), the steep pyramid (311) being usually better developed than the flat pyramid (111). Peculiarly shaped inclusions are of frequent occurrence, especially in the prismatic grains. Many of the zircons are colourless.

Tourmaline.—The brown variety of this mineral is that more usually found, though blue tourmaline does occur. The grains may be in rounded, or in prismatic form.

Apatite.—The grains of this mineral are often common and their shape is oval, or, sometimes, almost spherical.

Monazite.—Greenish-yellow grains, very well rounded and showing broad dark borders in consequence of their high refractive index, are common in nearly all the samples examined.

Staurolite.—The presence of this mineral has been detected in all the samples treated and it commonly occurs as large grains, the surfaces of which are coated for the greater part by iron compounds. In acid-cleaned sand the mineral appears beautifully fresh and, while it shows marked pleochroism, it is usually straw-yellow in colour to almost colourless. Grains with a jagged outline are characteristic, but tabular, prismatic and even rounded grains do occur. The mineral differs markedly from the poor iron-coated and usually small examples of the same mineral occasionally found in the Coal Measure sandstones of South Yorkshire.

Ilmenite is a mineral of common occurrence and is far more abundant than magnetite.

Rutile.—Usually as oval grains and sometimes as long prisms is occasionally present.

White epidote in prisms, muscovite flakes, anatase and, far more rarely, grains of sphene are encountered.

These minerals, which accompany the barytes in the Nitticarhill sandstone, are found in the Carboniferous rocks to the west. Moreover, barytes is not rare as a joint-filling mineral in the Coal Measures of South Yorkshire and Derbyshire, though no large deposits of the mineral such as those found in the Coal Measures at the New Brancepeth and Ushaw Moor Collieries, 3 to 4 miles west of Durham,[1] have yet been found. It is probable therefore that the direct source of the detrital barytes in the Permian sand is to be traced to the Coal Measures rather than to the gangue barytes of the lead-zinc veins of the Carboniferous Limestone, though its present exposure is less than 20 miles away. One reason for supposing the direct source of the barytes not to have been the Carboniferous

[1] *Mem. Geol. Surv. Reports on the Mineral Resources of Great Britain*, vol. ii, 1922, pp. 11–13, Barytes and Witherite.

Limestone veins of Derbyshire is based on the absence of fluorite from the Lower Permian Sands, as fluorite invariably accompanies barytes in the limestone veins and would endure transport better than barytes itself.

It is of interest to note that in a recent paper to the Liverpool Geological Society, Miss M. Workman records no barytes and no staurolite in the Lower Permian Sands which she examined from South-West Lancashire on the western side of the Pennines.[1] The general presence of staurolite in the South Yorks and North-East Derbyshire sands tends to exclude the possibility of these sands having been directly derived from rocks as old as the Millstone Grit. Professor Gilligan does not record staurolite among the minerals described by him from the grit north of Sheffield.[2] He also emphasizes the absence of apatite from the Millstone Grit as individual grains, though he finds it present in the granitic boulders.[3] This mineral is common in its occurrence in the Lower Permian Sand. Many of the "Grits" west of Sheffield have a cement which is partly of barytes and it is reasonable, therefore, to suppose that the detrital barytes in particular and the Lower Permian Sands of South Yorkshire and North-East Derbyshire in general have their source mainly in the Coal Measures to the west of their present outcrop, though the abundance of garnet and monazite point to the inclusion in the sands of some material having its source in the Millstone Grit. Hence some, at least, of the barytes in these older rocks may be of pre-Permian or at latest Lower Permian age.

It is not inferred that detrital barytes is present in the Permian Basal Sand at all the localities in the region under notice, and the above evidence merely establishes its very local occurrence under certain conditions. Fragments of barytes are, however, common in nearly all the samples of South Yorkshire and Derbyshire Lower Permian Sand which I have examined, but it is exceedingly difficult, or even impossible, to prove the detrital nature of barytes in a loose sand and, therefore, the preservation of the detrital barytes in the Nitticarhill sandstone may be regarded as a fortunate coincidence.

Submarine Erosion off the Holderness Coast.

By C. Thompson, Hymers College.

THE effects of erosion above high-water mark are obvious to all and much has been written thereon. That erosion also takes place below high-water mark is not nearly so evident. A study of the successive editions of the Ordnance Survey maps, especially those drawn to the 6-inch scale, would show at once that submarine erosion must be taking place off Holderness.

[1] Geol. Mag., vol. lx, 1923, p. 142.

[2] Dr. A. Gilligan, "The Petrography of the Millstone Grit of Yorkshire": *Q.J.G.S.*, vol. lxxv, 1920, p. 251.

[3] Op. cit., p. 272.

For the information of those who are not well acquainted with the nature of the Holderness coast and adjacent sea floor, the following short description is given.

Inland borings made near the coast prove that at a depth of about 130 feet we come to the solid Chalk. Above that there is *no solid rock*. All is softer material, so that this particular sea floor consists of Boulder clay and other glacial or post-glacial deposits. The Boulder clay is a compact, tough, and fairly homogeneous substance, but it is interspersed, here and there, with comparatively small masses of sand and gravel. The probability is that it will erode less easily than soft clay like the Oxford Clay or the Speeton Clay, to the north and south of Filey respectively, but far more quickly than the hard sandstones, Lias shales and limestones; witness the scars at Robin Hood's Bay, Whitby, and Redcar.

Therefore, submarine erosion must vary greatly along the Yorkshire coast, the rate being governed largely by the nature of the sea floor. Off Holderness we have uniform conditions extending for a greater area than anywhere else to the north, off our county. Therefore, what is taking place here should be instructive as a general indication of what must be taking place in variable degree under other conditions. The destructive action of boring organisms is probably more effective in Chalk, shale, and limestone than in Boulder clay.

In the years 1903–4, R. G. Allanson Winn in several very important papers drew attention to this coast. His papers were illustrated by sections drawn on a small scale and proved that what he calls "deep water" erosion must be taking place. These papers attracted much attention and caused some local perturbation.

Last year, Mr. G. W. Lamplugh suggested to the writer that he should investigate the inshore movement of the 30-ft. line. In consequence of that suggestion many charts and maps have been examined. Lines were then chosen for the drawing of sections showing, by means of exaggerated gradients, the relative positions of the sea bed at different dates during a period of ninety-four years. It is hoped that the sections given will enable the inshore movements of the various depth-lines to be visualized.

In regard to the 30-ft. line, the result of the inquiry was not conclusive. This is due to two causes. Where the soundings are frequently revised there is much movement of drifting material. Outside that area the chart-makers seem satisfied with Captain Hewett's 1828 survey. This is probably due to the fact that only small fluctuations take place on our very gently inclined sea bed below the 30-ft. line. It follows that there are not enough data at present available to write anything definite about that line for the coast in question. One ought to add, however, that Mr. Cheverton Brown reported to the Royal Commission on Coast Erosion that he could find no difference in the positions of his 30-ft. soundings after an interval of some years.

Between that particular line and H.W.M. the various maps and charts are very full of information for places near the Humber Mouth; less so to the north. The only sections yielding reliable results down to the depth in question are those lying between the southern flank of Dimlington Height and the spit of sand and shingle forming Spurn Point. To the north of the Height we can

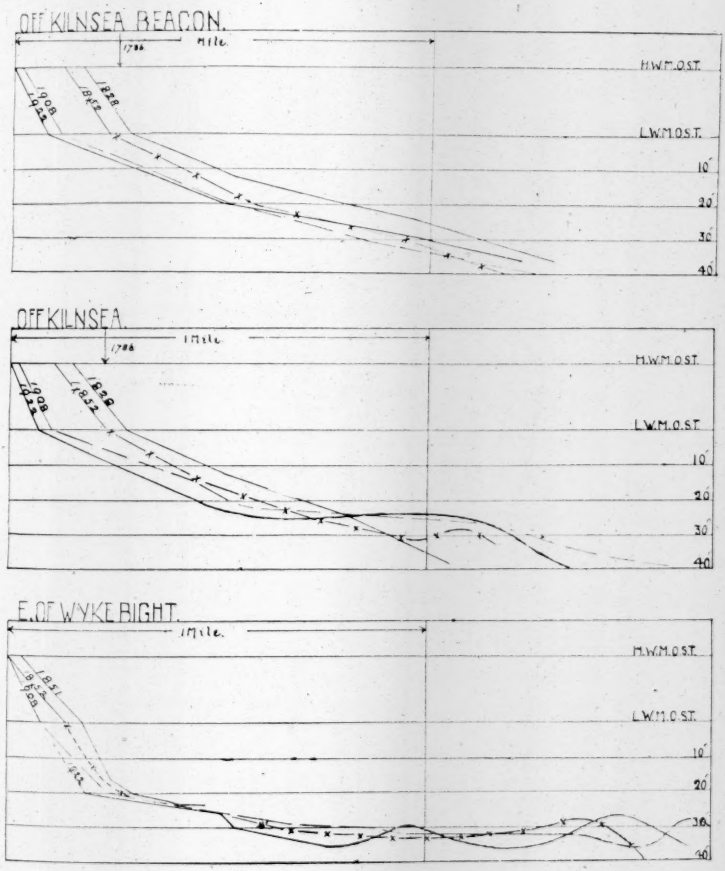

FIG. 1.—Comparative sections showing submarine erosion at different localities off the Holderness coast.

get from the 6-inch maps the inshore creep of H.W.M. and L.W.M., but the charts give us the soundings of the 1828 survey only.

In all the sections drawn (of which three follow) the positions of the 1908–9 and the 1852 H. and L.W.M.'s are drawn directly from fixed inland points on the 6-inch maps of those dates. The

1828 and 1922 lines are put in from the writer's own annual averages for cliff erosion during the past seventy years, so that they may be taken as approximations. Below the L.W.M., in each case, the soundings are taken from the various Admiralty charts of the given dates and their distances all plotted to one uniform scale (6 inches to 1 mile).

An examination of the sections shows that in every case, where the movement is not checked by groynes, the H. and L.W.M. both follow the destruction of the cliff fairly regularly. Where the cliff is most rapidly eroded, there the westward creep of the H.W.M. is most rapid; in fact, in the writer's opinion, it is not going too far to say that the average rate of advance is directly as the average rate of destruction and removal of cliff.

The L.W.M. keeps about the same distance from the H.W.M. in their simultaneous advance. Of course, there must be variations due either to temporary accumulation or to temporary sweeping away of beach materials.

In the Kilnsea area this westward movement for the ninety-four years may be taken as 10 feet per annum and the erosion of the area between these lines as a deepening of about 4 inches per annum. This deepening is due chiefly to wave and surf action but the movements of drift material must also contribute to the final result.

Everywhere below the L.W.M. there is a distinct lowering of the rate of erosion down to the 30-ft. line; near to which it may be said to die away. Outside that line, the depths fluctuate slightly from year to year. This can only be accounted for by the irregular movements of low mounds of drift material, such as sand and shingle, in these shallow waters.

One and a quarter miles south of Kilnsea, off the bend of the Spurn spit known as Wyke Bight, there has been a very rapid advance of the 30-ft. line and a general slight deepening below that line since 1908; as if much drift material which had collected near the spit had been scattered further afield. This is the only definite advance of that debatable line which the writer has to report.

The effect of groyning is well shown in the section off Wyke Bight and also one drawn off Withernsea. In each case we get the westward creep of the H.W.M. stopped and even reversed owing to the very pronounced banking up of the sand, etc. It is to be noted, however, that erosion still goes on seaward of the bank; so the gradient between H.W.M. and say a depth of 25 feet becomes steeper and steeper. Hence, ultimate disaster.

When the 1786 cliff line of Tuke is plotted it appears that now in some places there is about 10 feet of water over the site even at low water. If we consider the L.W.M. of 1852 we find that to the south of Hornsea it had already crossed to the westward of the cliff line of Tuke's time. Finally, the site of the 1852 cliff is now permanently under water off Kilnsea, but this is the only area where such rapid erosion has taken place.

Summary.

1. Submarine erosion off Holderness is a fact, as pointed out by Winn.

2. The rate is greatest between H. and L.W.M.'s.

3. Between L.W. and 20 feet it is much less rapid.

4. Below 20 feet it still further diminishes to the 30-ft. line; outside which it apparently dies away.

5. Groynes—taking the long view—are unfortunately only a temporary safeguard for this district of easily eroded clay.

The writer's sincere thanks are due to Mr. G. W. Lamplugh, F.R.S., for his very kind and keen interest in the work.

The Metamorphism of the South-West Highlands.

By E. B. Bailey, M.C., B.A.

Introduction.

LAST year, I published a theory of the structure of the South-West Highlands in which was included a short statement regarding the metamorphism of the district (1922, p. 92). It seems that movement and metamorphism in this particular region have been too closely contemporaneous to allow of a tectonist deriving much assistance, in the initial stages of his work, from a study of the metamorphic condition of the various rocks with which he has to deal. There is no suggestion anywhere of contrasted metamorphisms having been brought into contact as a result of thrusting. If, as I suppose, there have been great thrust-movements, these must, for the most part, have occurred before the conclusion of the metamorphic period.

The general failure of my supposed thrusts to interrupt the metamorphic gradients of the district may be taken in conjunction with their very restricted development of mylonitization, a feature which has occasioned much adverse comment on the part of critics. I am of opinion that this relative absence of mylonitization merely indicates temperature-conditions favourable to crystallization during and after the period of movement. In some cases, however, appearances of mechanical destruction remain a prominent feature of the thrust-planes of the district. Two easily located examples are afforded by (1) the Appin Quartzite just above the Ballachulish Thrust, or Slide, in its eastern outcrop on the north side of Loch Leven (Sheet 53 of the 1-inch Map of Scotland), and (2) the exposures of the thrust-plane at the base of the Iltay Nappe in the Ardmucknish peninsula (1922, p. 112; 1922a, p. 302).

The close time-connexion between metamorphism and movement, which I imagine has been demonstrated, makes it imperative to consider these two subjects in conjunction; and in this direction I find myself impelled to follow closely in Clough's footsteps, although often I seek help from others as, for instance, Cunningham Craig, and occasionally I strike out a line of my own.

The present paper recapitulates, without argument, the leading features of my structural conception of the South-West Highlands; and, from the standpoint thus defined, it reviews the many observations and theories hitherto advanced in regard to the metamorphism

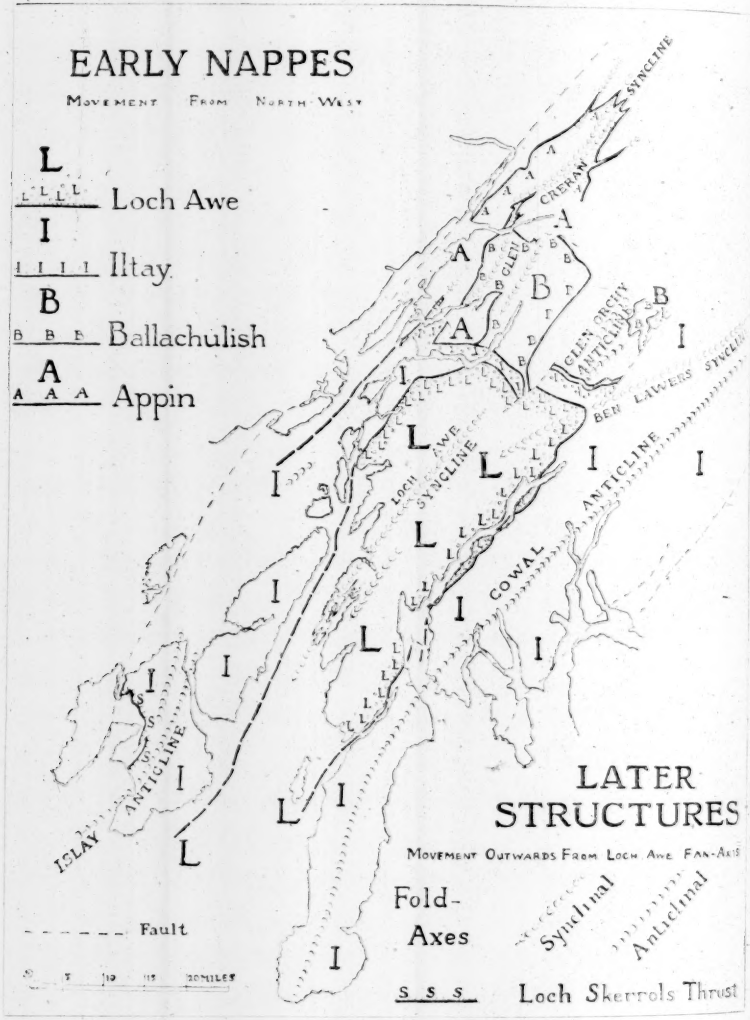

Fig. 1.—The Nappes of the S.W. Highlands.

of the district. My function is mainly that of a commentator, and my principal object is to render the rather difficult literature of the subject more accessible to fellow-workers both at home and abroad.

Structure.

The rocks of the South-West Highlands can be assigned to three great structural divisions which, in descending order, are as follows (Fig. 1) :—

Loch Awe Nappe.
Iltay Nappe.
Ballappel Foundation { Ballachulish Nappe. / Appin Nappe. / Sub-Appin Complex.

The movements which developed these nappes came from the north-west.

The Loch Awe Nappe is preserved as an outlier, or klippe, in the heart of the Loch Awe syncline. The last named is everywhere a complex structure ; and, in a north-easterly direction, it encounters the Glen Orchy Anticline and splits into two definitely separated branches the Glen Creran Syncline, on the north-west, and the Ben Lawers Syncline, on the south-west.

The Loch Awe Syncline is flanked by two important anticlines named after Islay and Cowal respectively.

The formation of these synclines and anticlines occurred after the nappes as such had come to rest. The movements involved in their production seem to have been directed outwards from the axis of the Loch Awe Syncline. This complex syncline is itself of fan-type, and the Islay Anticline on its north-west side has been overthrown towards the north-west, while the Cowal Anticline on the south-east side has been overthrown towards the south-east. The Loch Skerrols Thrust of Islay has been developed in the overturned north-west limb of the Islay Anticline ; it is tentatively correlated with the Moine Thrust of the North-West Highlands.

The mapping of the various superimposed nappes, and of the synclines and anticlines by which they have been affected (Fig. 1), is of importance to the student of metamorphism, since it furnishes a rough indication of the relative depth of cover under which crystallization may be supposed to have taken place. It cannot, however, be too clearly stated that individual nappes vary greatly in thickness from place to place. For instance, the Ballachulish Nappe, locally about 2,000 feet thick, disappears altogether beneath the north-west corner of the outcrop of the Iltay Nappe ; and this latter is itself very much thinner where it emerges on the north-east side of the Loch Awe Nappe than it is either in Islay or in Cowal.

Metamorphism.

Zonal Distribution.

At this stage it may be helpful to quote, with verbal alteration, five paragraphs which have already appeared in the *Quarterly Journal of the Geological Society* (1922, p. 92) :—

(1) Fig. 2 furnishes a graphical statement of the metamorphism of grey pelitic (or semi-pelitic) sediments in the South-West Highlands.

(2) In such rocks, metamorphism leads from slates and phyllites through mica-schists into either garnetiferous mica-schists or albite-schists.

(3) In rocks of a different composition (as, for instance, quartzite, limestone, or even carbonaceous or calcareous pelitic sediments) response to metamorphic influences may not agree very closely with what is shown in Fig. 2. Thus, the Ballachulish Quarries yield black roofing-slate, although situated on the margin of the garnetiferous zone of Fig. 2 (1916, p. 202).

(4) A vague agreement between the outcrops of successive metamorphic and structural zones, respectively, lends distinct support to a theory of metamorphism controlled by depth-temperature, such as was developed

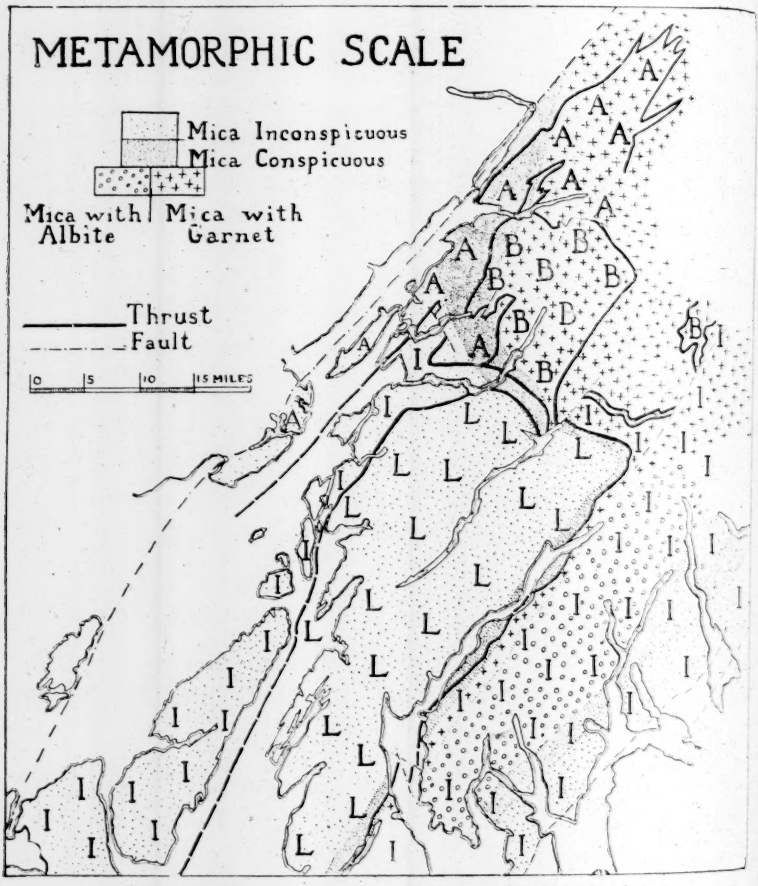

Fig. 2.—Metamorphic Areas of the S.W. Highlands.

by Clough (1897, p. 91) to account for the relatively high metamorphism characteristic of the axial belt of the Cowal Anticline (Figs. 1 and 2).

(5) The agreement noted above is so incomplete that no increase of metamorphism accompanies the emergence of nappes north-west of the Loch Awe and Glen Creran Synclines. This capriciousness suggests recourse to Barrow's theory of metamorphism controlled by temperature dependent upon magmatic distribution (1893, 1912). I know of no reason against combining Clough's and Barrow's interpretations.

In further explanation of (4) and (5), it may be pointed out that Barrow does not believe in the existence of Clough's Cowal Anticline. For him the rise in metamorphic intensity often encountered along the denuded crest of the anticline is entirely due to the vagaries of magmatic distribution. Parenthetically, it may be mentioned that Barrow has the credit of being the first Scottish geologist to draw a metamorphic map of the type of Fig. 2. In preparing Fig. 2 itself, I have borrowed freely from publications by Clough, Hill, Cunningham Craig, Peach, and others, supplementing their statements where necessary out of my personal knowledge which embraces most of the district.

Cunningham Craig, it should be realized, does not agree with Barrow in the latter's regulation of Cowal metamorphism by magmatic distribution; although he is at one with him in disregarding Clough's evidence for the existence of the Cowal Anticline. His theory of metamorphic control is briefly as follows: during the onset of earth movement, closely packed steep isoclinal folds developed on either side of what Clough terms the axial belt of his anticline, while the rocks along this intervening belt happened to remain relatively unaffected; then shearing movement took the place of folding, and the flat beds of the axial belt proved defenceless against its attack, while their steeply packed neighbours on either side in large measure escaped unhurt; with the shearing, or perhaps later, came thermal and hydrothermal metamorphism, the manifestations of which were directly proportional to the preparatory destruction due to shearing, and therefore especially pronounced among the rocks of the "flat belt" (1904, pp. 11–13).

I can only add that I am convinced by Clough's account of the Cowal Anticline as a fold affecting previous isoclinal folds and attendant foliation. I also feel that Clough is justified in attributing much of the high metamorphism characteristic of the axial belt of his anticline to the depth of cover which erosion in this position has since removed. One may add that, if the Cowal Anticline is admitted in Cowal itself, it must also be admitted as extending from coast to coast of Scotland, though generally with its south-east limb steeply inverted.

The low metamorphism of the Loch Awe klippe at first sight appears nothing more than a continuation of the story of decreasing metamorphism outwards from the axis of the Cowal Anticline, and has been interpreted in this fashion by Mr. J. B. Hill (1911, pp. 83, 84). The rise of metamorphism in a north-easterly direction, where pitch leads to successive emergence of the Iltay Nappe and Ballappel Foundation from below the Loch Awe Nappe, is also in close agreement with Clough's theory of increase of metamorphism with increase of original depth of cover. On the other hand, Clough's theory, if construed too narrowly, gives no explanation of the relatively low metamorphism which is a feature of the north-west margin of the district illustrated in Fig. 2. For instance, in

Islay, where according to my reading of the structure, the Iltay Nappe emerges from beneath the Loch Awe Nappe, there is no tendency to a recurrence of the grade of metamorphism characteristic of Cowal; and, in like manner, as one proceeds north-eastwards from Islay, though one certainly does meet with a general increase of metamorphism corresponding in some measure with the successive emergence of lower nappes, this increase is always much delayed as compared with what is encountered along a parallel line farther south-east, say through Loch Awe. Incidentally, one may note that the lack of agreement between the outcrops of the various metamorphic and structural zones in this region of relatively backward metamorphism affords an opportunity of studying particularly convincing examples of progressive metamorphism. Thus, the type-outcrop of the Leven Schists lies in the Appin Nappe, and can be traced for about 40 miles from Ardmucknish in the south-west to Glen Roy in the north-east: in the former district, the rocks are in the condition of phyllite; north-eastwards they become mica-schists; at Loch Leven, they occasionally include garnets; while in Glen Roy they are profusely garnetiferous and often carry biotite-pseudomorphs after actinolite.

I suggest that the above facts find their most satisfactory generalization in the following proposition:—

The metamorphic zones of the South-West Highlands are superimposed upon one another in order of increasing crystallization from above downwards. The surfaces separating the various metamorphic zones are often gently, though distinctly, inclined with reference to the surfaces separating the various tectonic zones or nappes; and, through much of the district, their relative inclination is downwards towards the north-west.

Barrow would, I am certain, deny the significance of the structural divisions I have traced; and therefore it is difficult to institute a comparison between his views of metamorphic distribution and the one communicated above. His outlook is best considered independently. He pictures the Highlands as having acquired, at a late stage in their original history of movement, a widespread metamorphism zonally grouped about certain dispersive centres of intrusion; he also thinks that the interior metamorphic zones thereafter reacted as relatively rigid bodies during subsequent disturbances, and were apt to part company along their margins with more yielding adjacent sediments. In this way Barrow thinks he can account for the position of some of the most important dislocations of the country; for instance, the Moine Thrust of the North-West Highlands, the Great Glen Fault, or Thrust, as he prefers to call it, forming the north-west boundary of the district under consideration (1917, p. 159), and the Highland Border Thrust which he regards as the approximate south-eastern limit of the same (1912, p. 283). I confess I have never been able to detect any close agreement between the straight course of the Great Glen Fault and

the curved outcrop of the metamorphic zones, which, as shown in Fig. 2, clearly abut against it.

Albite-Schists.

In a very considerable area of Fig. 2, increasing metamorphism has led to widespread development of albite-schists, or gneisses, in which albite often figures as small porphyroblasts. Teall first investigated these rocks microscopically and chemically, and instituted valuable comparisons between them and previously described occurrences from the Eastern Alps, Saxony, and Massachussetts (1897, pp. 297, 299). The question of the origin of the albite-schists and gneisses of the South-West Highlands has been mainly discussed by Clough and Cunningham Craig. They have both taken up the standpoint that the albite-schists are a product of the metamorphism of sediments; but, whereas Clough seems to admit the possibility of "considerable chemical changes, and a large impregnation of soda" (1897, p. 39), Cunningham Craig discounts any such suggestion. Exactly what Clough had in mind when he wrote of a possible impregnation of soda is uncertain. At any rate, both authors agree that in the area examined, some 40 miles long by 10 broad and dissected by valleys approaching 3,000 feet in depth, there is no trace of an igneous intrusion which could be held responsible for albitization of the sediments concerned. Clough's own words are: "The albites are of regional occurrence, and are found independently of any visible igneous rock" (1897, p. 101). The granite complex of Garabal Hill (Glen Fyne) does indeed fall within the zone, but its obvious contact-effects, such as the development of andalusite, etc., are confined to an aureole measuring about a mile outwards from its own margin (1897, p. 101); while the albite-schists reach for fully 20 miles beyond this limit. The albites in the contact-aureole are always altered in appearance, and sometimes, according to Cunningham Craig, are replaced by other minerals.

When it is said that there is no trace of an igneous rock which could be held responsible for albitization, some critics may possibly disagree. Pegmatite veins, consisting of albite and quartz, with or without chlorite, are a feature of the albite-schists. They are generally quite thin and to be measured in inches or less; but in one locality they are several feet broad and traceable for yards. They are apt to carry tourmaline as an accessory, a mineral also met with in the matrix of the albite-schists (1897, p. 40). In the absence of any more definite evidence of magmatic intrusion, the very reasonable interpretation has been adopted that these pegmatites are a product of the metamorphism, and have been derived from the sediments which they traverse.

Clough regarded the albite-schists of the South-West Highlands as altered pelitic sediments. In Cowal, he says, "the albite-spots are almost confined to the more micaceous or chloritic beds: it is doubt-

ful whether they occur at all in the quartzose pebbly beds" (1897, p. 39). Although many of the albite-schists can certainly be claimed as in a broad sense pelitic, there can be little doubt that Clough formed an exaggerated opinion in this respect. For instance, he

	I.	II.	III	*x*.	IV.	A.	B.	C.	P.	Q.
SiO_2 . .	43·3	63·4	65·11	65·9	77·22	64·70	64·35	62·40	60·15	78·6
TiO_2 . .	1·2	tr.	0·83	0·8	0·59	0·59	0·70	0·81	0·76	0·2
Al_2O_3. .	26·2	18·1	15·78	15·4	10·07	15·45	16·54	16·27	16·45	4·7
Fe_2O_3. .	13·6	6·7	6·49	7·2	4·02	1·36	2·24	1·44	4·04	1·0
FeO . .						4·18	3·92	5·78	2·90	0·9
MnO . .			0·24		0·30	0·05	0·14	0·35	tr.	tr.
MgO . .	3·8	1·9	1·95	2·0	1·17	1·48	2·04	2·19	2·32	1·7
CaO . .	0·5	0·9	1·34	0·9	1·10	2·92	2·04	2·07	1·41	3·3
BaO . .						0·10	0·11	0·07	0·04	0·0
Na_2O .	1·8	3·2	2·49	2·4	2·65	3·09	2·00	2·28	1·01	0·5
K_2O . .	4·6	3·2	3·97	3·3	2·65	3·46	3·82	3·16	3·60	1·3
P_2O_5 . .			0·25		0·14	0·19	0·17	0·16	0·15	0·0
CO_2 . .			0·39		0·32	0·85	0·13	0·52	1·46	5·4
$H_2O+105°$ or 110°.	4·5	2·8	1·41	2·0	0·36	1·82	1·73	2·25	3·82	1·2
$H_2O-105°$ or 110°.						0·15	0·12	0·16	0·89	0·3
SO_3 . .									0·58	0·0
S . .			0·14			0·05		0·04		
C . .								0·10	0·88	
	99·5	100·2	100·39		100·59	100·44	100·05	100·05	100·46	100·2

I. Green Phyllite; Ben Ledi Grit and Schist Group; Blairmore, Cowal; Anal. J. J. H. Teall. Quoted from C. T. Clough, "Geology of Cowal": *Mem. Geol. Surv.*, 1897, p. 39.

II. Porphyroblastic Albite-Schist; Ben Ledi Grit and Schist Group; Stuck Burn, Cowal; Anal. J. J. H. Teall. Quoted from C. T. Clough, ibid., p. 39.

III. Albite-Gneiss; Ben Ledi Grit and Schist Group; Rudha Ban, Loch Lomond; Anal. W. Pollard. Quoted from Cunningham Craig, *Quart. Journ. Geol. Soc.*, 1904, p. 23.

x. Mean of I and IV in the proportion 1 : 2.

IV. Schistose Grit, or Greywacke; Ben Ledi Grit and Schist Group; Rudha Dubh, Loch Lomond; Anal. W. Pollard. Quoted from Cunningham Craig, ibid., p. 23.

A. Porphyroblastic Albite-Schists; composite analysis of six specimens; Stavanger district; Anal. O. Röer. Quoted from V. M. Goldschmidt, *Geologisch-Petrographische Studien im Hochgebirge des Südlichen Norvegens*, vol. v, 1921, p. 84.

B. Coarse grey Quartz-Muscovite-Biotite-Garnet-Schists; composite analysis of four specimens; Anal. O. Röer. Quoted from V. M. Goldschmidt, ibid., p. 75.

C. Brown Quartz-Muscovite-Biotite-Garnet-Schists; composite analysis of six specimens; Anal. O. Röer. Quoted from V. M. Goldschmidt, ibid., p. 72.

P. American Palæozoic Shales; composite analysis of 51 specimens; Anal. H. N. Stokes. Quoted from F. W. Clarke, *Bull. U.S. Geol. Surv.*, No. 168, 1900, p. 17.

Q. American Sandstones; composite analysis of 253 specimens; Anal. H. N. Stokes. Quoted from F. W. Clarke, ibid., p. 17.

selected for chemical comparison a thoroughly pelitic phyllite of the Ben Ledi Group of Grits and Schists (I of the Table, outside the albite-region) and a porphyroblastic albite-schist of the same great heterogeneous group (II, within the albite region). He was evidently disappointed in the contrast which analysis revealed; and it was in this connexion that he remarked on the possibility of superimposed chemical change.

Cunningham Craig looked rather to felspathic grits, or greywackes, for the origin of the albite-gneisses. Accordingly, he chose for comparison III, a typical albite-gneiss from Loch Lomond, and IV, the coarsest and most siliceous grit obtainable at Rudha Dubh, on the shore of the same loch, but situated outside the albite-region. He points out that a less pronounced grit would probably have given a much closer approximation to III than is shown by IV. The justice of this claim is emphasized by the resemblance which x bears to III. I feel, in the light afforded by x, that a mixed series of greywacke and shale, of which IV and I are representative members, must be expected to contain some proportion of greywacke-shale of a composition corresponding with II and III.

The reasonable nature of this inference is strengthened when one notices that the Loch Lomond greywacke (IV) carries six times as much Na_2O as the average American sandstone (Q), whereas the albite-schists (II and III) contain respectively only three and two and a half times as much Na_2O as the average American Palæozoic shale (P).

Accordingly, though I am ignorant of the ground, I am prepared to adopt what is virtually Cunningham Craig's position, and suggest that *the albite-schists and gneisses of the South-West Highlands have resulted from metamorphism of greywacke-shales; and that, though migration of material has certainly occurred, it is only on a small scale and of a strictly intraformational character.*

The source of the authigenic albite is, according to Cunningham Craig, to be looked for in the felspar pebbles that are a conspicuous feature of the greywackes of the Ben Ledi group. These pebbles have commonly been spoken of as oligoclase, but my own experience is that they are essentially albite accompanied by a proportion of more or less perthitic orthoclase. One of the many distinctions between the albite pebbles and the albite porphyroblasts is the tendency to lamellar twinning exhibited by the former and absent in the latter.

There would have been no need to elaborate upon Cunningham Craig's exposition of this side of the subject had it not been for recent work by Goldschmidt in another part of the Caledonian chain. The three composite analyses, A, B, and C, from the Stavanger district of Norway bear an obvious resemblance to II and III from the South-West Highlands of Scotland; in fact, their only noteworthy difference is a higher content of CaO. It is rather disquieting to find that Goldschmidt has derived the rocks represented by A, B,

and C through contamination of an associated quartz-muscovite-chlorite-phyllite; he pictures this phyllite as having suffered an immigration of SiO_2, CaO, and Na_2O, and a loss of H_2O; and he regards the added material as having had its source in a complex laccolithic intrusion of soda-granite, or trondhjemite (1921, pp. 110, 113, 114). The differences, however, in the two cases seem much more real than the resemblances. The scheme of mineral-development is not the same; and rocks of the type represented by A, B, and C, appear to be restricted to within 2 km. measured outwards from the trondhjemite margin (1921, pp. 48, 49). At the same time it must be admitted that Goldschmidt is dealing with an exceedingly difficult problem: his trondhjemite complex is intruded as a composite laccolith along a stratigraphical boundary between green-schists above and phyllites below (1921, p. 36); and accordingly the supposed felspathized schists occupy a high position in the phyllite group, while the unaltered phyllites with which they are chemically compared occur distinctly lower down in the series. To an onlooker, it seems just possible that beds of soda-rich grey-wacke-shale may have been an original feature of the phyllite-group near its junction with the overlying sedimentary, volcanic, and intrusive rocks, now classed together as green-schists. Moreover, south-east of a line drawn north-west through Stavanger, the typical habit of the trondhjemite laccolithic complex is to lie with mylonitized base in advance of the more definitely metamorphic zones found farther north-west, and in immediate superposition on quartz-muscovite-chlorite-phyllite (1921, p. 38). The thrusts of this region are interpreted as disappearing north-westwards; but their local well-marked presence certainly adds to the perplexities of the general situation.

The strength of Goldschmidt's position depends upon the obvious thoroughness of his investigation, combined with the apparent continuity which he is often able to detect in the various stages connecting phyllite with injection-gneiss, and finally with trondhjemite.

Albitic and Garnetiferous Metamorphisms contrasted in the South-West Highlands.

Cunningham Craig points out (1904, p. 26) that the albitic facies characteristic of so much of the Ben Ledi and adjoining groups in Cowal is not a necessary outcome of their progressive metamorphism; he has traced the Ben Ledi group in the Aberfeldy district of the South-Central Highlands from a region of low metamorphism, near the Highland border, into one characterized by muscovite-biotite-schists, or gneisses, with a considerable number of large and well-developed garnets, "where nothing like the albite-gneisses has been observed."

In the north part of Cowal, garnets are found in force a little north-west of the albite-area. The boundary separating the belts character-

ized by the two minerals is fairly well marked, though everywhere interrupted by marginal trespass (1897, cf. pp. 41, 48). North-east of the head of Loch Fyne, the limit falls within the Ben Ledi group; but farther south garnets are almost entirely restricted (in pelitic rocks) to the Ben Lui group, until at last, on the shores of Lower Loch Fyne, they fail to be prominent in this or any other position (1897, p. 49).

Cunningham Craig is of opinion that in the garnet-zone much of the Na_2O finds its way into white mica, or paragonite, instead of albite. The point obviously requires attention in future chemical work in the garnet-zone.

Cunningham Craig offers a suggestion to account for the observed antithesis between garnet and albite in the South-West Highlands. He suggests, and I agree, that *garnet bespeaks a more thermal, and albite a more hydrothermal, condition of regional metamorphism.* In this connexion, he lays stress on the characteristic association of biotite with garnet, and of chlorite with albite (1904, p. 27).

The next question that arises is whether the garnetiferous and albitic metamorphisms of the South-West Highlands have been contemporaneous or successive. The answer to which I have been led is that *the two metamorphisms probably continued in operation side by side for a considerable period, although eventually the albitic survived the garnetiferous.* My reasons are as follows :—

(1) If the two metamorphisms are not in part contemporaneous, then, as Clough has clearly shown, the albitic must be the later. Clough has demonstrated that the garnets of the north-west flank of the Cowal Anticline are very commonly " rodded " (an expression which is illustrated in Fig. 3), while the albites of the albitic axial belt are in large measure later than the final intimate movements of this district (1897, p. 52). Now, if the albitic metamorphism is altogether later than the garnetiferous metamorphism, it would be an unlikely coincidence that its operation should have terminated, geographically speaking, along an original boundary of the garnetiferous zone; so that one would expect to find frequent relics of garnet replaced by chlorite even in the heart of the albitic region. Any such relics as may exist have escaped Clough's notice, except in the admittedly garnetiferous zone.

(2) The albites certainly seem to have flourished after the garnets ceased to grow, but at the same time they often carry internal evidence of early initial generation, which it is eminently reasonable to suppose dates back to the same period as the adjacent garnetiferous metamorphism. This side of the question is discussed in the final section of the present paper.

Metamorphic Succession.

It is impossible to proceed further without directing attention to a very interesting aspect of Clough's work in Cowal (1897). He separated, as I think quite correctly, two great stages in the movement-history of the district leading respectively to :—

(1) A series of isoclinal folds with two characteristics in common : (*a*) the main foliation of the district lies parallel to their axial planes; (*b*) those among them closing towards the south-east exhibit a preferential thinning of their under limbs.

(2) The Cowal Anticline which, on a large scale, arched up the foliation mentioned under (1).

The early isoclinal folds and accompanying foliation, where they lie comparatively flat along the axial belt of the Cowal Anticline, are affected by innumerable little folds and puckerings, with which are associated strainslips dipping steeply towards the north-west. Clough very reasonably correlates these relatively late folds and fractures with the development of the Cowal Anticline. His conclusions in this respect gain support from somewhat analogous observations by Wright in Colonsay (1908), and myself near Glen Nevis (1910, p. 604).

Some may doubt the time-correlation of the axial disturbances and the Cowal Anticline; but all must admit that these disturbances give an opportunity of establishing certain stages in the metamorphic history of the district. Clough has taken advantage of this opportunity, and has pointed out, for instance, that micas, chlorite (1897, p. 76), and tourmaline (1897, Figs. 29, 30), bent and fractured by the puckerings and strainslips, must have grown at an earlier date than associated undisturbed segregations of albite and quartz, with or without chlorite and tourmaline, which themselves remain quite unaffected by these movements (1897, p. 40).

Rotation Alternative to Rodding.

The following proposition brings into correlation certain aspects of the chemistry and dynamics of metamorphism.

Where one or other of the minerals albite or garnet is enclosed in a schist subjected to shearing stress it may respond either by deformation of the type known as rodding or else by rotation (Fig. 3). Rodding occurs where the mineral is in a figurative sense "dead", and therefore a comparatively easy prey to disintegration. Rotation occurs where the mineral is "alive" and actively growing; in this latter case, chemical attraction seems to endow the crystal with additional powers of resisting deformation by disruption, so that, instead of shearing in company with its deformable matrix, it merely rotates.

Rodding consists in a notable elongation in a particular direction approximately parallel with the planes of foliation. Clough's descriptions show that the rodding of felspar pebbles (which, I presume, are albite) is largely accomplished through a development of transverse cracks (or crevasses) now occupied by quartz deposited from solution.[1] His illustrations, of which one is reproduced in Fig. 3, are drawn from greywacke-schists outside the albitic zone of metamorphism (1897, Figs. 5–7). He states very definitely that similar rodding nowhere affects the albite porphyroblasts of the albitic zone. In regard to these latter, he writes: "It is not uncommon for the rows of inclusions in the albites to run in a different direction

[1] The process of rodding may be pictured by imagining the separation of a pebble into two parts through the opening of a transverse fracture under shearing stress. In such a case, the front part of the pebble with the matrix in front of it moves forward with the overlying layer of matrix, while the back part of the pebble with the matrix behind it moves backward with the underlying layer of matrix.

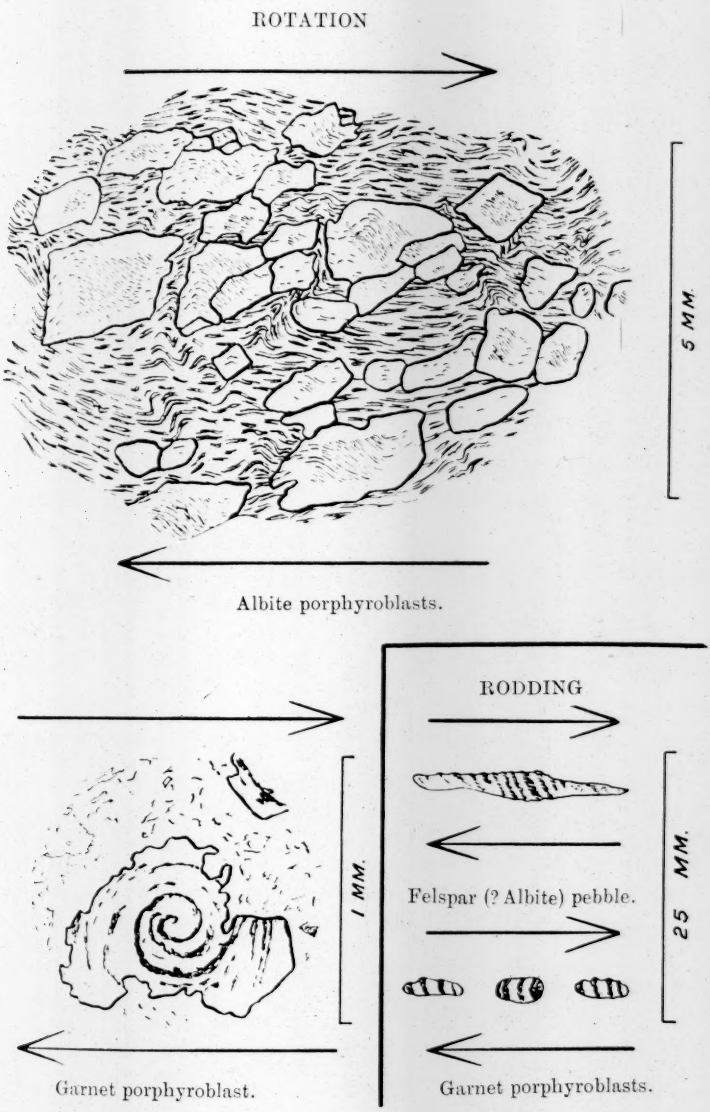

FIG. 3.—Arrows indicate shearing stress. The rotated albite porphyroblasts are drawn from Geol. Surv. slice 3418, from which a single porphyroblast has already been figured by Teall (1897, Pl. VI, Fig. 1). The rotated garnet porphyroblast is drawn from a photograph (Flett, 1912, Pl. IX, Fig. 6). The rodded felspar and garnets are after Clough (1897, Figs. 7 and 23); the clear spaces in these rodded minerals are occupied by granulitic quartz.

from the foliation of the rock enclosing them. The inclusions show the direction of foliation at the time of the formation of the albites, but there is a suggestion that the albites may have received a twist" (1897, p. 43). So far as I know, these discordant foliation relics are only found preserved in the early-formed kernels of albite porphyroblasts, the marginal portions of which are often remarkably free from enclosures. Teall illustrates such a case (1897, Pl. VI, Fig. 2), where there is a pronounced discordance between the foliation-directions exhibited in the kernels of adjacent albite-porphyroblasts. It is well to realize these irregularities, since they are to be expected according to the theory of rotation; in fact, one cannot often hope to meet with so extraordinarily simple a slice as is illustrated in Fig. 3. There may seem no need to comment upon the rotation during growth of the porphyroblasts in this particular case; but it happens that Clough for once missed the significance of evidence of the type which he had made peculiarly his own. He claimed that the movements recorded in this slice are earlier than the unbroken, unstrained albite porphyroblasts, since "the puckered foliation planes of the rock" are "traceable through the albites by the help of frequent inclusions" (1897, p. 40). Fig. 3, however, shows that the lines of inclusions pass through the individual porphyroblasts according to a very definite plan: it is clear, in fact, that, towards the end of the growth-period of their kernels, the porphyroblasts suffered a right-handed rotation; and that what were at the time unenclosed adjacent foliation planes were pulled down on the right-hand side of each rotating albite crystal and up on the left.

When one passes to a consideration of garnet in this connexion, one finds that Cowal supplies many instances of rodding, but that it is necessary to go to another district of the Highlands to find examples of rotation. Clough has figured rodded garnet porphyroblasts which are in every way similar to the rodded felspar pebble illustrated in Fig. 3 (1897, Fig. 23). More commonly, however, he found the deformation of garnets to be accompanied by partial or complete replacement by chlorite (1897, Fig. 22). The only clear instances of rotated garnets with which I am acquainted come from the North-East Highlands, and have been illustrated and described by Flett (1912*a*, Pl. IX, Fig. 6, and p. 111). He remarks, in relation to a particular schist, that the enclosures in the garnets "may even form spiral rings which can be traced, making a complete revolution within a single crystal. The explanation of this peculiarity seems to be as follows:—The garnet was rotating under the impulses received from streams of material flowing with unequal velocities past its two sides. It was being rolled along, and was growing larger, like a snowball, during the process".

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The Base of the Devonian, with special reference to the Welsh Borderland.

By L. DUDLEY STAMP, B.A., D.Sc., A.K.C., F.G.S.

(*Continued from p. 282.*)

IV. DESCRIPTION OF TYPICAL SECTIONS IN WALES AND THE BORDERLAND.

The classification set forth in this paper is founded essentially on an examination of the junction-beds between the Silurian and the Devonian in the field. All the localities described have been studied personally by the writer, and in most cases the actual junction has been mapped on the 6-inch scale. The names of localities are taken from the 6-inch Ordnance Survey maps, the sheet number being quoted in each case.

1. *Long Mountain* (6-inch Ord. Surv. Shropshire, XL, N.E.).

On the Geological Survey map (1-inch, Old Series, Sheet 60, N.E.) an inlier of Old Red Sandstone about a mile in length is indicated to the south-east of the village of Middletown. Professor W. W. Watts has suggested that the "Old Red Sandstone" was probably

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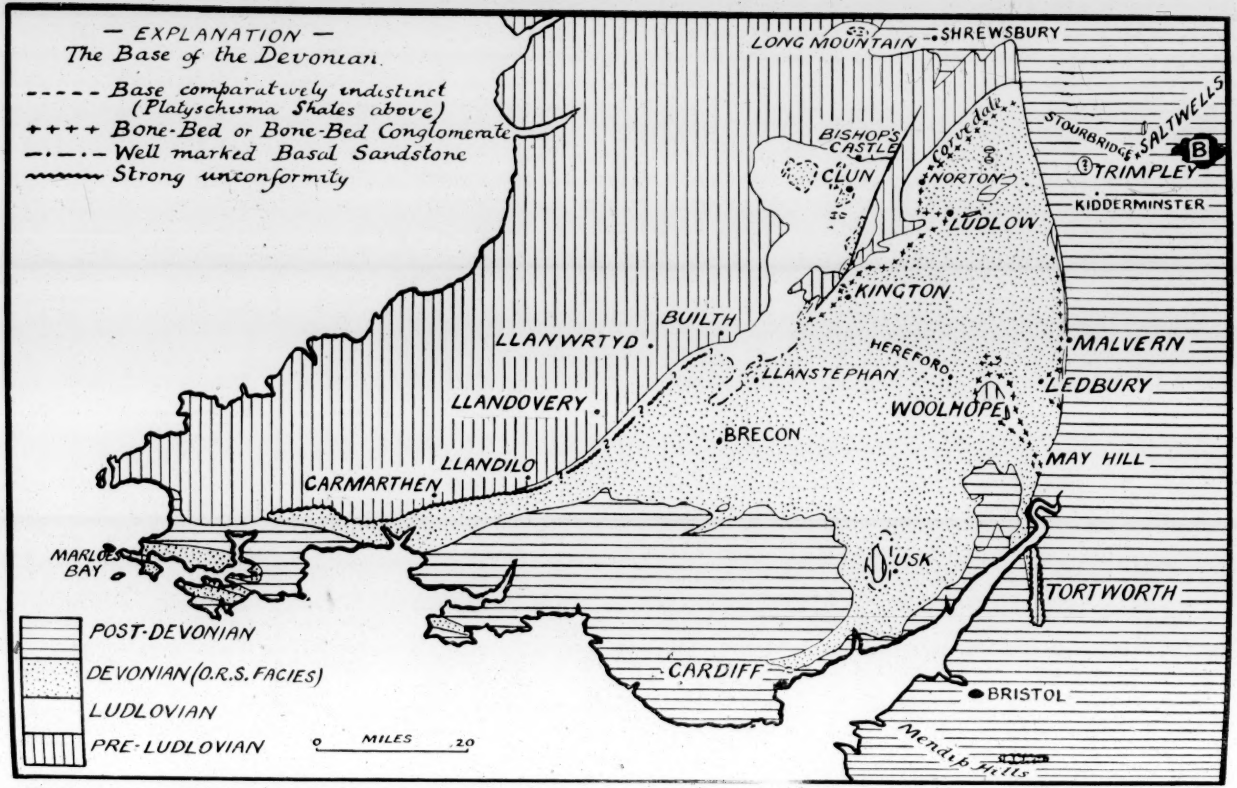

FIG. 1.—Geological sketch-map of South Wales and the Borderland, showing the relative position of the localities mentioned in the

homotaxial with the Temeside Shales of the Ludlow District, and mentioned the presence of " Passage Beds ",[1] but the existence of true Upper Ludlow Beds of Shropshire type appears to have remained unknown.

LUDLOVIAN. The Lower Ludlow Shales, which surround the basin-shaped inlier, have been mapped and described by Miss E. M. R. Wood (Dame E. Shakespear). They are succeeded by hard flags and " cardboard shales " with *Dayia navicula* and *Cardiola* (Aymestry Group). The overlying *Rhynchonella* Beds are Calcareous flags with *Rhynchonella nucula*, *Orthonota amygdalina*, *Serpulites longissimus*, etc., and can be seen on the lower parts of the scarp-slopes of Cheshire's Wood (northern side of syncline) and of Oakley Wood (southern side). The *Chonetes* Beds are more arenaceous, especially in the upper part, than in the Ludlow district. *Chonetes striatella* occurs in the lower part, but the higher, more sandy flags are very sparingly fossiliferous. These beds can be seen on the northern slopes of Hargrave Bank.

DOWNTONIAN. The Ludlow Bone-bed is represented by a thin sandstone band crowded with *Bellerophon trilobatus*, broken fragments of *Lingula* and some fish-remains (*Thelodus parvidens* and ? *Onchus*). Above it are a few feet of " silvery " shales with *Platyschisma helicites* and *Modiolopsis complanata*, and bands crowded with *Beyrichia*. The succeeding sandy beds (Downton Sandstone)—of which the lower part, together with the underlying lowest Downtonian beds, is poorly exposed in the old ditch along the crest of Hargrave Bank—are thinly-bedded, micaceous tilestones, becoming more massive in the upper part. Their outcrop is marked by a line of old shallow quarries along Hargrave Bank and the northern edge of Broomhill Wood. Eurypterids and *Eukeraspis pustulifera* occur, and *Lingula minima* is abundant in the lower beds. One of the writer's former students, Mr. J. E. Austin, B.Sc., has undertaken the more detailed examination of the Long Mountain, and he has discovered a good section of the lowest Downtonian in a tiny faulted inlier near Wallop Hall. The Temeside Shales—the highest beds in the inlier—have the same characters as near Ludlow.[2] They consist of rubbly, olive-green shales, and near the base include several layers crowded with *Lingula cornea*. An old quarry (at a higher horizon) by the roadside near Mountain Farm yielded *Lingula cornea*, a large species of *Leperditia*, *Beyrichia*, and lamellibranchs.

2. *Clun Forest* (South-West Shropshire).

The writer has already published a detailed account of the geology of the south-eastern part of this region.[3] The Ludlow Bone-bed was not detected, but the assumption then made that the silvery

[1] Lapworth & Watts, " Shropshire " in " Geology in the Field " : *Jub. Vol. Geol. Assoc.*, 1910, p. 756.
[2] Elles & Slater, op. cit., p. 204.
[3] Stamp, op. cit., *supra*, 1918.

Platyschisma Shales represented a deeper water facies of the Downton Sandstone has now been proved to be correct. Bone-beds with typical Downtonian fish-remains have been discovered near the base of the shales, though probably slightly above the horizon of the Ludlow Bone-bed.

(*a*) *Clun Outlier.*

LUDLOVIAN. *Rhynchonella* Beds. There is little to add to the description of these beds previously given.

Chonetes Beds. These beds consist of irregularly bedded calcareous flags passing up into more evenly bedded flagstones and then into thinly bedded brittle shales. The latter sometimes have numerous tiny flakes of mica, giving them a silvery appearance, and they then resemble the *Platyschisma* Shales. Whilst the bulk of the latter in the Bucknell area (of the writer's former paper) is certainly equivalent to the lower part of the Downton Sandstone, it is just possible that the lowest beds there should be grouped with the *Chonetes* Beds. At Mainstone *Chonetes striatella* "*Rhynchonella nucula* (small form)" (probably *Retzia bouchardi*) and *Spirifer elevata* occur abundantly in the shales at the top of the *Chonetes* Beds.

DOWNTONIAN. The Ludlow Bone-bed has been recorded from Mainstone, about 3 or 4 miles south-west of Bishop's Castle. The record is vague: " . . . after tea the geological members of the party walked to see the Ludlow Bone-bed, which was well exposed ",[1] but Mr. Parry, of Bishop's Castle, who was one of the excursionists, informed the writer that the bone-bed was seen along the lane at the eastern end of Knuck Wood, south-west of Reilth, and about half a mile south of Mainstone School (Shropshire, LXII, S.W., 2nd. Ed., 1903). The section starts in a small quarry near the southern end of the wood, and successive lower beds are seen as one descends towards the ford, but exposures are poor. The section is as follows[2]:—

	ft.	in.
Fragments of Tilestones.		
Coarse greenish sandstone, breaking somewhat irregularly (fractured and recemented) . . . . . about	6	0
Silvery or thinly banded *Platyschisma* Shales with lenticular bands of limestone (crowded with *Platyschisma helicites*, *Holopella*, etc.), especially in the upper part . . . about	30	0
Band of *Platyschisma helicites* and *Modiolopsis complanata* with fish-remains		3
Soft, thinly bedded mudstones	4	0
Band, crowded with *Beyrichia*		1
Soft, thinly bedded mudstones . . . . . seen for	6	0
Gap in section.		
Upper *Chonetes* Beds—shales with *Chonetes striatella*, "Rhynchonella nucula (small form)" and *Spirifer elevata* .		

[1] *Trans. Caradoc Field Club*, vol. i, pt. iv, issued for 1896, 1897, pp. 181-3.

[2] In this and all other tabulated successions the rocks are Downtonian unless otherwise stated.

The *Platyschisma* Band in this section, which is also a bone-bed, appears to correspond to the "Downton Bone-bed" of Elles and Slater.[1] It is probably the "Ludlow Bone-bed" recorded by the Caradoc Field Club, unless the true Ludlow Bone-bed is hidden in the soft, thinly bedded mudstones below the *Beyrichia* Band. The true Ludlow Bone-bed in the Ludlow district and in neighbouring areas always occurs *below* the lowest *Platyschisma* Bed and the *Beyrichia* Bands. The slight uncertainty on this point does not effect the main importance of the section. The lowest *Platyschisma* Band is a bone-bed with Downtonian fish-remains, therefore the overlying *Platyschisma* Shales are Downtonian in age and equivalent to the lower part of the Downton Sandstone. The following fossils were obtained at Mainstone [2]:—

Beyrichia Band: 30, 34, 39.
Platyschisma Band: 1, 4*a*, 7, 44, 47, 51.
Platyschisma Shales (in a lenticular band of limestone, partly weathered to a "rottenstone" in the quarry, i.e. about 25 feet above the lower band): 4*a* (abundant), 7, 17 ?, 42, and 44 (fragments), 51, 54, 55, 58 ?.

The *Platyschisma* Shales are well exposed in an old quarry half a mile to the south-west of the last section, 300 yards west of New House (Shropshire LXII, S.W.). The beds dip east at about 60°, and more than 60 feet are exposed. The limestone lenticles here are of great interest and yield a fauna which is obviously a mixture of the shallow water species (*Platyschisma, Bellerophon*) usually found in the lower part of the Downtonian, and of deeper water Ludlovian species (*Chonetes, Discina, Orthoceras*). The latter are more varied than in the Downton Sandstone. The fossils collected include:—30, 33, 34, 36, 37, 42, 51, 54, 55, 56, 57, 59 ?, and some large lamellibranchs. An interesting sequence can be made out in a hilly field 400 yards north-east of Reilth. The *Chonetes* beds with the usual fossils; *Platyschisma* Shales with bands of rotten limestone with *Platyschisma* and *Modiolopsis*; and micaceous sandstones (Downton Sandstones) are all present. The shales are considerably affected by local folding, and dip at high angles along the ridge. A few yards to the east, and immediately to the other side of the hedge, typical rubbly olive-green Temeside Shales are seen. The sandstones yielded several specimens of *Cyathaspis banksii*, including a nearly complete cast and large well-preserved fragments. Other fossils noted are: 21 ?, 26, 44, 47a, 51, 52, 55a, 60.

Mr. Parry informed the writer that the "Ludlow Bone-bed" was formerly visible a short distance inside the margin of the wood ¾ mile east-north-east of Guilden Down, near Clun (Shropshire, LXIX, N.E.). Temeside Shales, seen in an old quarry within the wood, are the only beds now exposed. Mr. Parry also states

[1] Op. cit., p. 209.
[2] To economize space by avoiding the repetition of fossil names, the fossils recorded are indicated by numbers referring to the lists in a later section.

that the Bone-bed was to be found by careful search in the brook course nearly a mile north-east of Guilden Down.

To the west and south-west of Clun the Upper Ludlovian forms the heather-covered hills of Llanvair and Rock Hills (Shropshire, LXIX, S.W.). The beds dip on the whole northwards, and the northern slope of the latter hill is practically a dip slope of Upper *Chonetes* Beds. The *Platyschisma* Shales give rise to a hollow, but they are seen further west along Offa's Dyke just south of Springhill Farm. Beds belonging evidently to the Temeside Shales are exposed in various quarries along Weston Hills. The beds quarried are usually strongly false-bedded, micaceous, greenish sandstones. Slightly further north the *Platyschisma* Shales are well exposed in and near the stream above Lower Spoad, and bands of broken *Lingulæ* are here frequent (Shropshire, LXIX, N.W.). The shales are again considerably affected by minor folding, a feature not to be seen in the harder beds above and below. Similar crumbling was recorded in the Five Turnings Outlier,[1] and is seen also at Woodside, south-east of Clun (Shropshire, LXIX, S.E.). In the last-mentioned locality the *Chonetes* Beds occur to the east and the Temeside Shales to the west of the valley, and it seems that part of the shales have been cut out by "crush faulting", which is really an extreme case of the minor crumbling of these "incompetent" beds.

On the northern slope of Whitcott Evan Hill near the point marked "Old Quarry" on the 6-inch map (Shropshire, LXIX, N.E.), a spring issues from a small cliff. The rocks here exposed consist of red sandstone with fish-remains. The sandstone appears to belong to one of the higher fish-bearing horizons of the "Red Downtonian".

(*b*) *Bettws-y-crwyn Outlier.*

A greater thickness of Devonian sediments is present here than in the Clun Outlier, and the existence of Dittonian as well as Downtonian strata is probable. In a quarry a few yards north of the Anchor Inn (Shropshire, LXI, S.W.) fish-remains occur in the conglomerate base of a coarse green sandstone. They suggest one of the higher fossiliferous bands of the Downtonian which Mr. W. Wickham King is studying in Corvedale. In old quarries near Rhuddwr and Nant-y-rhynau (Shropshire, LXI, S.W.), especially the former, both Downton Sandstone and Temeside Shales are to be seen. The former is a hard yellowish sandstone with *Platyschisma helicites*, *Modiolopsis*, and abundant fragments of *Lingula minima*; the latter are soft greenish-grey shales full of plant-remains (many dichotomously branched resemble *Psilophyton*) and with bands of hard sandstone containing *Lingula cornea*, Eurypterids, *Modiolopsis*, and various lamellibranchs.

[1] Stamp, op. cit., 1918, p. 238.

(*To be continued.*)